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STRATEGIC PETROLEUM RESERVE (SPR)
SITE CHARACTERIZATION REPORT
WEST HACKBERRY SALT DOME

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INTRODUCTION

SPR PROGRAM DESCRIPTION

The Energy Policy and Conservation Act (EPCA) enacted in December 1975 provided the legislative authorization for the Strategic Petroleum Reserve (SPR). The objective of the SPR is to store substantial quantities of crude oil in order to diminish US vulnerability to the effects of a severe interruption in supply. The current plan for the SPR consists of three phases that, when complete, will provide the US with a 750-million-barrel (MMB) reserve. The legislation authorized up‘to a l-billion-barrel reserve, but plans have not been completed for the last 250 MMB.

The Phase 1 portion of the reserve uses existing storage volume at five sites. Four of the sites (Bryan Mound, TX: West Hackberry, LA; Sulphur Mines, LA; and Bayou Choctaw, LA) have solution-minded caverns that were originally created to produce brine as chemical feedstock, and the fifth site (Weeks Island, LA) has a conventional salt mine. The total existing capacity of these five sites is 248 MMB. Phase 2 plans are to expand the Bryan Mound and West Hackberry sites by solution-mining 12 and 16 additional caverns, respectively, of 10 MMB each. Plans for the remainder of the storage capacity to reach to 750 MMB reserve are under review by the US Department of Energy (DOE).

SANDIA SPR PARTICIPATION

Sandia National Laboratories, at DOE's request, made a short-term systems integration and engineering support study. The results have been published.[1] Several geotechnical recommendations resulted from the study, and Sandia was assigned the responsibility to provide a coordinated program of geotechnical investigations to support continued development of the SPR. The geotechnical program will provide a sufficiently comprehensive, site-specific data base to support the planning, design, construction, and operation of SPR crude-oil storage facilities. These data will be used in assessing the long-term stability of SPR storage caverns and mines to minimize the potential for cavity failures that could result in significant environmental impacts, economic losses, or failure to withdraw oil when needed. A long-term monitoring plan will be developed that will assure maintenance of the quantity and quality of the stored crude oil in a readily recoverable condition. The geotechnical program includes the following activities: geological site characterization; engineering design assistance and evaluation, including numerical simulation studies; laboratory and bench-scale testing of salt cores from SPR sites; monitoring and interpretation of field events; and instrumentation evaluation and development. These efforts pertain to the five sites currently in the SPR program. An additional task to provide interim technical support for leaching the first five three-well caverns at the Bryan Mound site was added by the SPR Project Manager's Office (SPRPMO) to the Sandia SPR Geotechnical Program.

REPORT DESCRIPTION

Section I reviews cavern stability, integrity, and usability for both existing and planned caverns at West Hackberry. The early analyses were done by using typical material properties. Future analyses will be done by using the information reported in Sections II and III of this report. As these analyses are completed, results and recommendations will be published for the existing and planned caverns.

Section II of this report is a comprehensive geological site characterization study done by Woodward-Clyde Consultants for Sandia. The geological characterization was to be done in two phases. In the first phase, a comprehensive study would be prepared from existing data, and in the second phase, field programs would be used to gather specific information as needed. Section II represents the results of Phase 1 only.

Section III of this report summarizes the materials property work that has been done at Sandia and by contractors. Geophysical logs from wells at West Hackberry plus -2700 feet of core provide the information from which specific properties have been assembled for use in our analytical models.

SANDIA RECOMMENDATIONS RESULTING FROM GEOLOGICAL AND MATERIAL STUDIES

A Phase 2 geological field program will not be necessary to support development and operation of the existing and planned caverns. Sufficient understanding of the subsurface geometry and lithology was gained during the Phase 1 program when combined with the geophysical field program by Woodward-Clyde Consultants (reported in Seismic Reflection and Gravity Surveys, Strategic Petroleum Reserve Site, West Hackberry, LA, August 1980). As a result of the geophysical program, Well 112 was relocated from the northwest corner of the site to a position near Well 108.

Following are specific recommendations for West Hackberry.

- Design the expansion caverns to provide a sump that will accommodate -5% of insolubles from the salt.

- Establish a progran to monitor water quality and gas to assess the level of methane present in the groundwaters.

o Locate and characterize the abandoned Olin caverns if any locations for additional caverns are considered. [The abandoned Olin caverns do not now present any danger to the Early Storage Reserve (ESR) or expansion caverns.]

o Establish a program to monitor the condition of the well casings, especially near the salt-(cap rock interface. Incomplete data have indicated a possible corrosive reaction on several of the casings caused by water in this region.

o <u>Cavern 6</u>. Assuming that this cavern is recertified (testing is currently taking place):

1) Take high-resolution sonar caliper survey after each cycle.

2) Maintain 10 to 15 feet of oil at roof at all times, or use saturated brine in lieu of fresh water to cycle oil or limit the fresh-water cycles to three.

3) Maintain same type of oil in 6, 8, 9.

0 <u>Cavern 7</u>. No recommendation.

o <u>Cavern 8</u>. 1) Take high-resolution sonar caliper survey after each cycle.

2) Maintain same type of oil in 6, 8, 9.

0 <u>Cavern 9</u>. 1) Take high-resolution sonar caliper survey after each cycle.

2) Maintain same type of oil in 6, 8, 9.

0 <u>Cavern 11</u>. No Recommendation.

SECTION I

WEST HACKBERRY CAVERN STABILITY ISSUES

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ABSTRACT

Cavern stability, integrity, and usability issues regarding existing and planned storage caverns in the West Hackberry salt dome are reviewed. Previous studies are discussed, ongoing investigations are summarized, and data needed to support the assessments are described.

CONTENTS

ILLUSTRATIONS

INTRODUCTION AND SUMMARY

The US Strategic Petroleum Reserve (SPR) program currently uses four existing caverns in the West Hackberry salt dome near Lake Charles, LA for storage of crude oil. One additional cavern, not in use now because of an accidental blowout and fire in September 1978, should be ready for use early in CY 1981. Another 16 caverns are being developed there by the DOE (see Figure 1). This report summarizes current concerns and briefly describes previous work in assessing the stability, integrity, and usability of each cavern and the proposed new caverns.

There are many common issues of concern at each site--depressurization effects, long-term creep closure, etc. The techniques used to address concerns at one site apply at all sites.

A review of cavern stability issues for each SPR site was provided in Reference 1 in 1979. From this blueprint for action, Sandia National Laboratories began a program of geotechnical investigations to support the continued development of the SPR. Initial evaluations of cavern integrity have been based upon the use of generic or "typical" salt properties. These evaluations have attempted to bound concerns associated with creep-closure rates, depressurization of the caverns to zero surface pressure on the oil column, and pillar or web thickness. Concurrently with these evaluations, a materials testing program was begun to characterize the salt from each site. These data will be used in ongoing and future studies to more accurately represent the geomechanical response of existing caverns in the West Rackberry dome and to simulate additional caverns planned for the dome. Additional data on the failure or fracture of the salt will be required. These data also serve as input to the leaching-simulation activities by providing cavern-specific geological data. Initial evaluations of cavern integrity were based upon cavern spacing data and dome boundary locations of questionable accuracy. Site characterization activities (Section II) have now brought together accurate, consistent geological and geometrical data on sediments, cap rock, salt stock, and cavern locations that will be valuable in assessing stability concerns.

Site characterizations, and careful consideration of the numerical analyses made to date on West Hackberry caverns and caverns in other domes, have resulted not only in several useful observations about the existing caverns but have also helped define additional evaluations that are needed.

In its present configuration, each West Hackberry cavern currently used for storing crude oil is geomechanically stable and can be safely operated. Web-thickness concerns about West Hackberry Caverns 6, 8, and 9, however, will probably limit operational flexibility of the third, fourth, and fifth fresh-water drawdown cycles at these locations. The stability of the large gallery after these three caverns coalesce will be evaluated in order to assess their future stability. The months ahead will see reports from the ongoing simulation of the new caverns under construction at West Hackberry.

EXISTING CAVERNS AT WEST HACKBERRY

Table 1 summarizes the geometrical data regarding the location of the five existing caverns in the West Hackberry dome. Similar tables have been published previously by Tillerson for each SPR site: however, Table 1 contains new data obtained from the site characterization work. For the overall SPR program, the volumes of the West Hackberry caverns range from about 8 MMB to more than 12 MMB. Cavern heights vary from 158 to 1011 feet, and diameters from 250 to 1150 feet.

Cavern roofs vary from a depth of 2440 to 3230 feet below the surface, while maximum depths are between 3350 and 3760 feet. Because the geometry of a cavern (as related to vertical and horizontal distances to the dome boundaries and to adjacent caverns) largely governs its suitability for storage from a geomechanics viewpoint, these properties and ensuing ratios to the cavern diameter, D, have been recorded in Table 1. The parameters for the West Hackberry caverns (Table 1) are seen as the bounds on several of the parameters in the overall program.

The distance between adjacent caverns, P, is the current wall thickness (not the center-to-center spacing between caverns) used as a measure of the likelihood for cavern coalescence. The P/D ratio indicates the pillar width relative to cavity size and inversely relates to the intensity of the loading that might be felt in the pillar: i.e., a lOO-foot pillar between 500-foot-diameter caverns (P/D = 0.2) would be more intensively loaded than if the surrounding caverns at the same depth had only a diameter of 100 feet (P/D = 1).

The roof or back thickness, B (amount of salt between cavern roof and the cap rock), is important to cavern stability since the salt must be thick enough to ensure proper grouting of the casing. The B/D ratio indicates the thickness-to-span ratio for the cavern roof. As the B/D ratio decreases to well below 1.0, concern intensifies regarding how adequate the roof material is for transmitting loads from the cap rock to the cavern walls without developingtensile stresses.

Another parameter, E, that can limit the suitability of an existing cavern for the storage of crude oil is how near the caverns are to the edge of the dome. The salt near the edge of a dome is more likely to be locally fractured and to contain impurities than the salt in the interior of the dome.

Any linkage between geologic formations bordering a dome and caverns within the dome must be avoided since the product stored in a cavern could conceivably be lost. Proximity of caverns to the edge of the dome may therefore limit the number of withdrawal cycles of a cavern.

Engineering, construction, and storage activities at the West Hackberry site have been briefly described in annual SPR reports.[3-5] New wells have been drilled at the site to enhance the operating capabilities of the caverns. Before any storage of crude oil, each existing cavern at West Hackberry was pressure-tested and certified suitable.[6] In addition, sonar surveys were obtained, logs were run of casing integrity, cement bond, and temperature, and new casings were cemented into existing wells as needed.

WEST HACKBERRY CAVERN 6

Cavern 6 (Figure 2a) was reported at certification in 1977 to have a regular pan shape, a volume of 12.2 MMB, and a height of 153 feet. Its maximum diameter was 839 feet. A sonar caliper survey taken during recertification in May 1980 indicated a different shape--a thin pancake-like cavity at the top of the cavern 10 feet high and 1150 feet in diameter, and a saucer-shaped lower portion 150 feet high with a maximum diameter of 800 feet (Figure 2b). The latest volume is calculated as 8.1 MMB. This difference is associated with the quality of sonar caliper surveys: the latest survey used a high-resolution sonar caliper; therefore, the 1980 shape and volume are considered more accurate.

Cavern 6 experienced a sudden release of pressure in September 1978 when a packer blew out during workover. Damage to the cavern and/or the well casings could have resulted.

Recertification of this cavern has been under way since the first quarter of 1980 and should be finished before the end of CY 1980. Cavern 6 is estimated to be within 300 feet of the edge of the dome and within 450 feet of Cavern 9. The roof thickness over Cavern 6 is -1288 feet (B/D = 1.12). Without an oil blanket Cavern 6 will grow -90 feet in diameter with each fresh-water oil removal cycle and will therefore not be useful beyond three cycles. Additional cycles can be realized with an oil blanket 10 feet thick or through the use of saturated brine to displace the oil.

Cavern 6 exhibits one of the least desirable shapes for an oil storage cavern, which raises questions about its basic stability. Structural analyses by Sandia of creep and elastic properties of the salt have eased this concern and indicate that Cavern 6 is structurally stable. No catastrophic changes are expected in this cavern from significant events such as rapid pressure drops.

WEST HACKBERRY CAVERN 7

Cavern 7 (Figure 3) has a long cylindrical top section . 250 feet in diameter combined with a spherical lower section 430 feet in diameter and a slightly eastward preferred-leaching direction relative to the development well. The cavern, with a volume of 12.3 MMB, is the largest storage cavern at West Hackberry. It is at least 1000 feet from the edge of the dome (E/D = 2.33) and is separated from the nearest cavern (No. 6) by 545 feet (P/D = 1.27). The thickness of the salt roof is 577 feet (B/D = 1.34). The separation distances and the thickness of the roof are adequate for five cycles of operation at Cavern 7, since 231 feet of salt would remain between Caverns 6 and 7 after five fill/withdrawal cycles in which fresh-water was the displacement fluid.

The shape of Cavern 7 very nearly approaches the desired cylindrical shape, and the cavern is therefore considered structurally stable. No catastrophic changes are expected in this cavern.

WEST HACKBERRY CAVERN 8

Cavern 8 (Figure 4) has a long cylindrical top section 250 feet in diameter and a short cylindrical lower section 446 feet in diameter, with a slightly eastward preferred-leaching direction. The cavern has a volume of 10.1 MMB and is located over 1000 feet from the edge of the dome (E/D = 2.24). The thickness of the salt roof is "450 feet (B/D = 1.00). Cavern 8 is located within 160 feet of Cavern 9 (P/D = 0.36) and will coalesce with Cavern 9 during the third fresh-water cycle, as reported in the Gulf Interstate certification document.[6] Coalescence may occur sooner, as discussed under the section for Cavern 9. The same type of crude oil should be maintained in Caverns 8 and 9, and similar pressure profiles should be maintained.

Cavern 8 is considered structurally stable, and no catastrophic changes are expected in this cavern.

WEST HACKBERRY CAVERN 9

Cavern 9 (Figure 5) is irregularly shaped, with a 400-foot-diameter upper chamber necking down to -60 feet and entering a lower chamber 588 feet in diameter. There is a slightly southward preferred-leaching direction relative to the development well. The cavern had a volume of 8.9 MMB based on the May 1977 sonar survey at certification; however, the cavern was returned to Olin for further brining after certification and has not been resurveyed. The volume, and the diameter, must now be larger than at certification. The cavern is located well away from the edge of the dome, with Cavern 6 between Cavern 9 and the edge. The thickness of the salt roof is more than 1000 feet (B/D = 2.5). Cavern 9 is within 160 feet of Cavern 8, as discussed in that section. Caverns 9 and 8 will probably coalesce before three fresh-water cycles are completed, since the actual pillar thickness is now probably smaller than that reported at certification because of the Olin activity.

Structural analyses run by Sandia indicate the cavern, although very irregularly shaped, does not present any instabilities. Cavern 9 should not show any catastrophic changes during the life of the program.

WEST HACKBERRY CAVERN 11

Cavern 11 (Figure 6) is perhaps as close to the ideal cavern shape as can be obtained. It is cylindrical, with a diameter of 306 feet, a height of 815 feet (H/D = 2.66), and a volume of 8.5 MMB based on the June 1977 sonar survey (the cavern has not been surveyed since certification). The cavern is located well into the dome more than 1000 feet from the edge (E/D = 3.27) and more than 1000 feet from the nearest cavern (P/D = 3.27). With the development of the expansion caverns, 108 and 112 will become the closest neighbors but with pillar distances adequate for five fresh-water cycles.

Cavern 11 should not present any stability or catastrophic-change problems throughout the life of the program.

EXPANSION CAVERNS AT WEST HACKBERRY

As noted on Figure 1, 16 new caverns will be developed at West Hackberry for the SPR program. Leaching of these new caverns will begin in 1981. Each cavern should provide 10 MMB of storage space after initial leaching is completed and will have a volume of 20 MMB after five cycles of use. Although minor changes may have been made in the design of the cavern, the parameters presented in Reference 7 reflect the basic dimensions and concept for these new caverns. No roof stability concerns are anticipated since each cavern will have -500 feet of salt in the roof. From the viewpoint of structural stability, no edge-of-dome problems are anticipated for any of the new caverns.

It was established in Reference 1 that the development of the SPR represents a new step in storage cavern design: no other caverns exist as close together as the SPR caverns at a comparable depth. A P/D ratio of 1.8 is to be maintained in the West Hackberry dome.

A series of finite-element structural and thermal calculations are currently under way at Sandia to estimate the closure rates and pressure histories that will be experienced in the West Hackberry caverns. After these caverns are developed, additional simulations may be required where the geometry deviates significantly from the designed shape. Simulations of the leaching of the new caverns with the Solution Mining Research Institute SALT 77 numerical model have provided data for developing a leaching plan for the Bryan Mound caverns and can be used to develop the leaching plan for the West Hackberry caverns. These simulations would use the data from Sections II and III of this report and would provide the basis for later modifications to the leaching plan.

TABLE 1
GEOMECHANICAL DATA FOR SPR CAVERNS AT WEST HACKBERRY SITE
(DEPTHS AND DISTANCES GIVEN IN FEET)

Cavern Number	Year Constructed	Volume (mmb)	Type of Oil	Top of Cap Rock	Top of Salt	Casing Seat	Top of Cavern	Bottom of Cavern	Cavern Diameter, D	Cavern Height, H	H/D	Nearest Cavern	Distance to Nearest Cavern, P	P/D	Roof Thickness, B	B/D	Distance to Dome Edge, E	E/D
6	1946	8.1**		1598	1949	2632	3237	3395	1150	160	0.14	9	450	0.39	1288	1.12	300	0.26
7	1946	12.3	Sweet	1551	1965	2400	2542	3498	430	956	2.22	6	545	1.27	577	1.34	>1000	>2.33
8	1946	10.1	Sour	1515	1991	2402	2440	3451	446	1011	2.27	9	160	0.36	449	1.01	>1000	>2.24
9	1947	8.9	Sour	1550	2153	2402	3210	3561	588	351	0.60	8	160	0.27	1057	1.8	NA*	NA*
11	1962	8.5	Sour	1529	2056	2790	2945	3760	306	815	2.66		>1000	>3.27	889	2.91	>1000	>3.27

*NA - Not applicable since another cavern is between Cavern 9 and dome edge.
**Based on Sonar Caliper Survey of May 21, 1980.

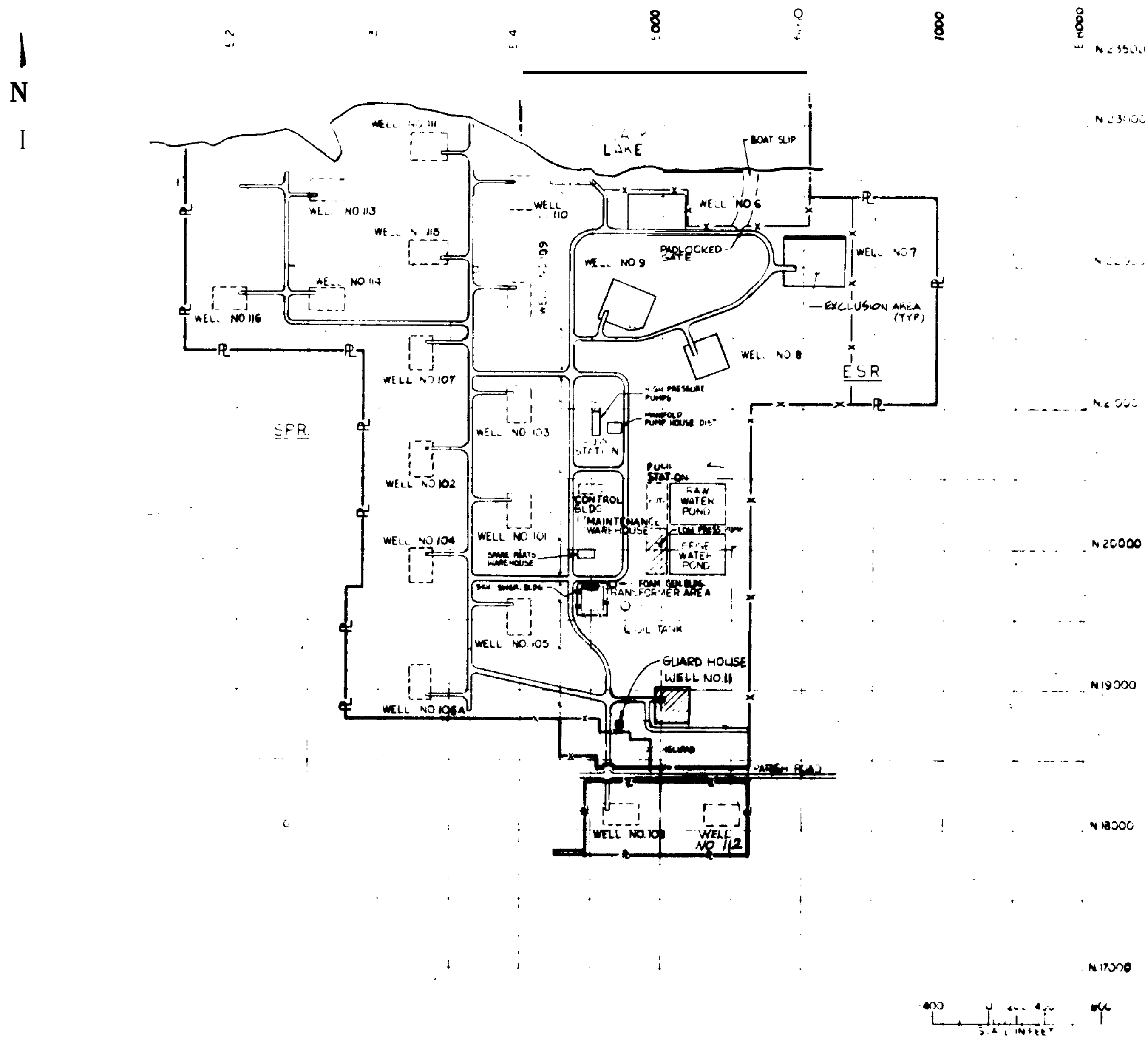

Figure 1.
WEST HACKBERRY CAVERN 7

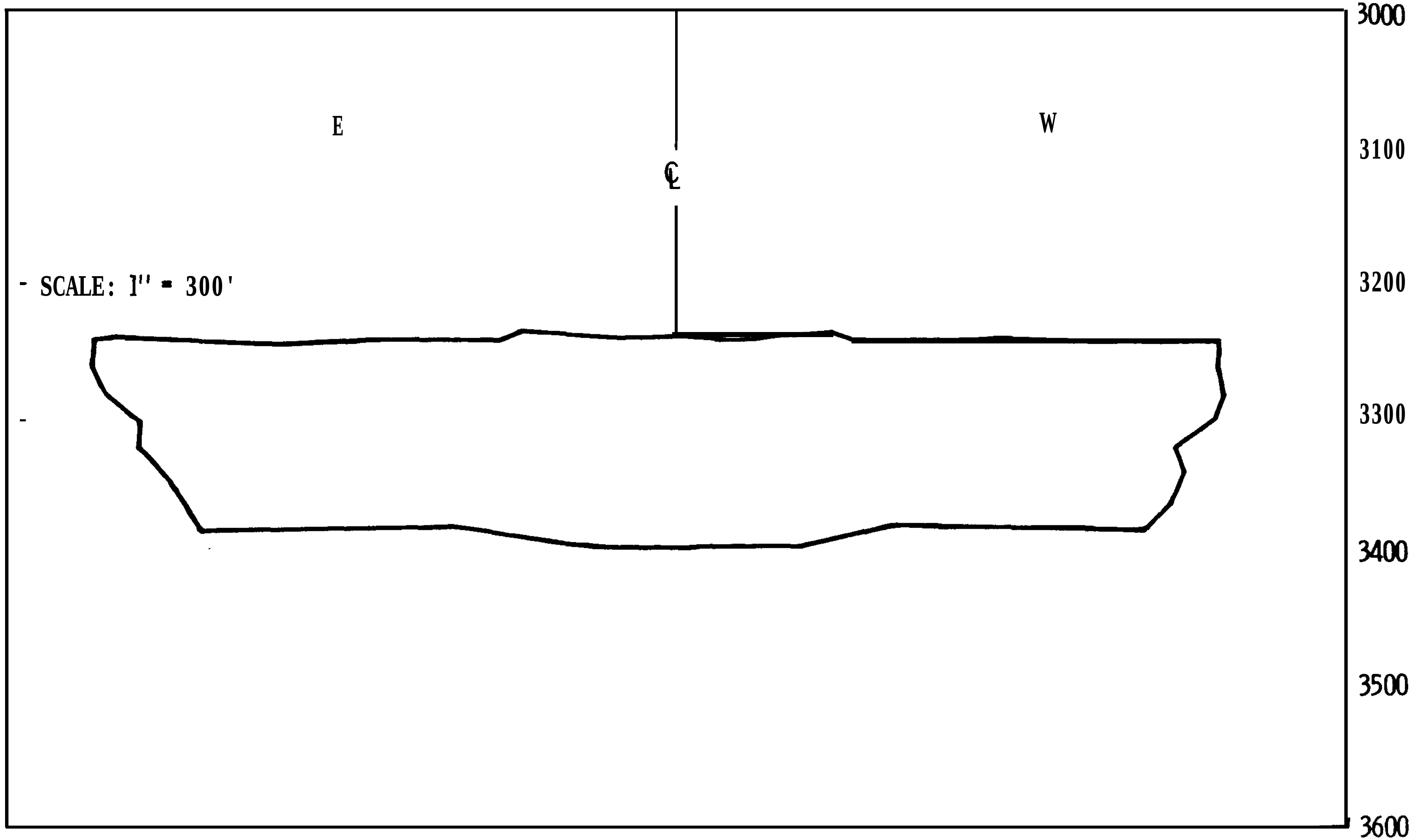

Figure 2a.

WEST HACKBERRY CAVERN 6
(1977)

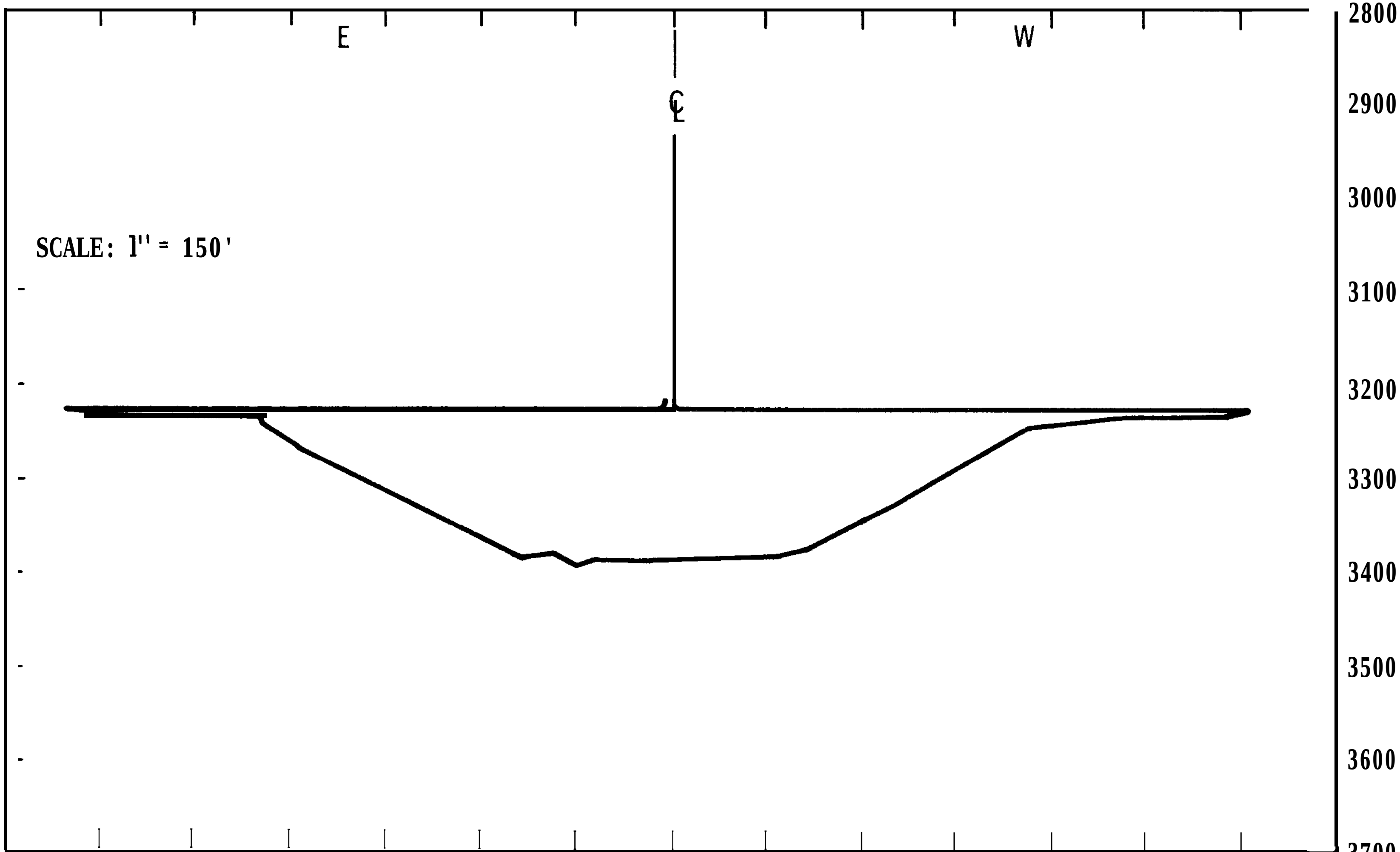

Figure 2b.
WEST HACKBERRY CAVERN 6
(1980)

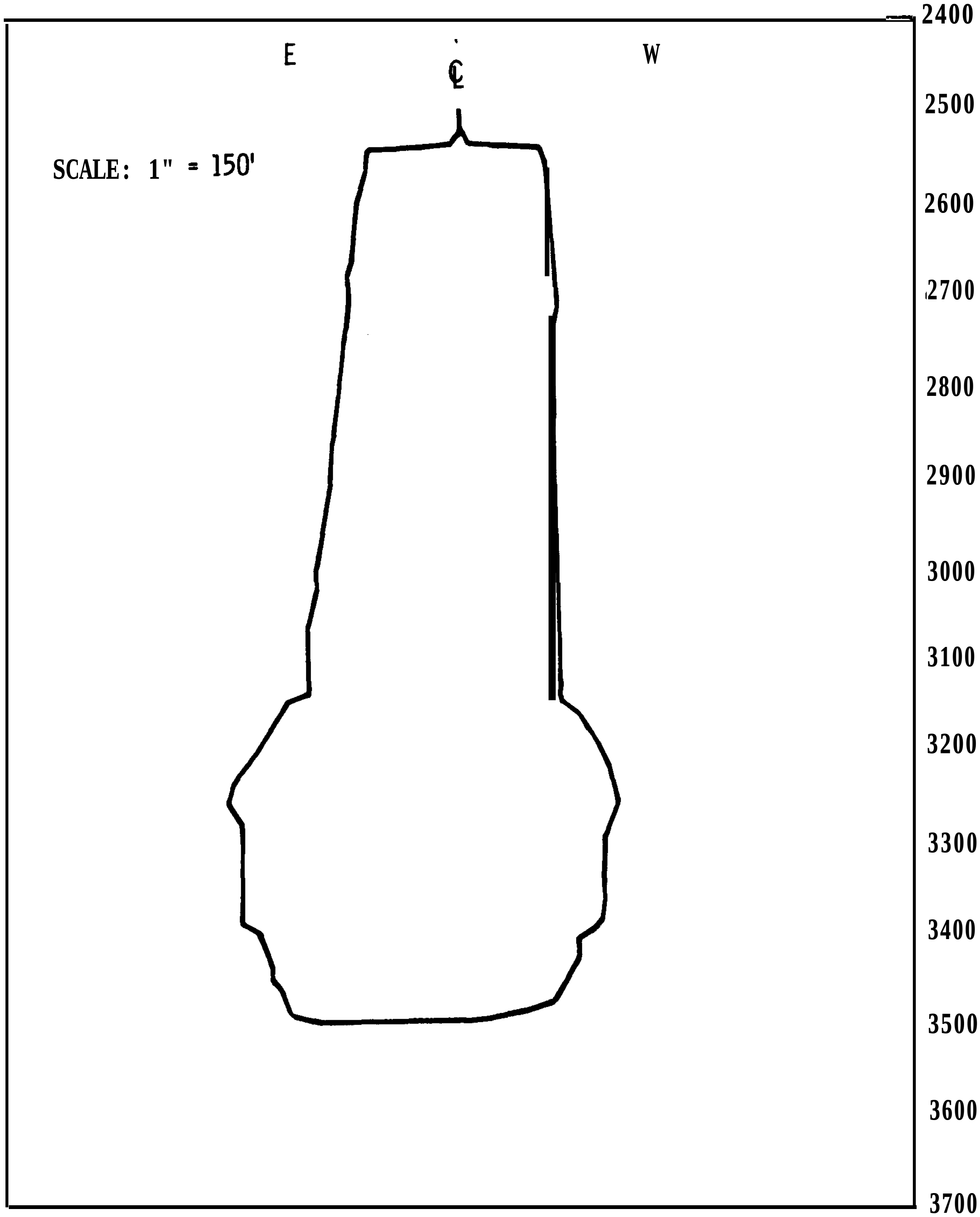

Figure 3.
WEST HACKBERRY CAVERN 7

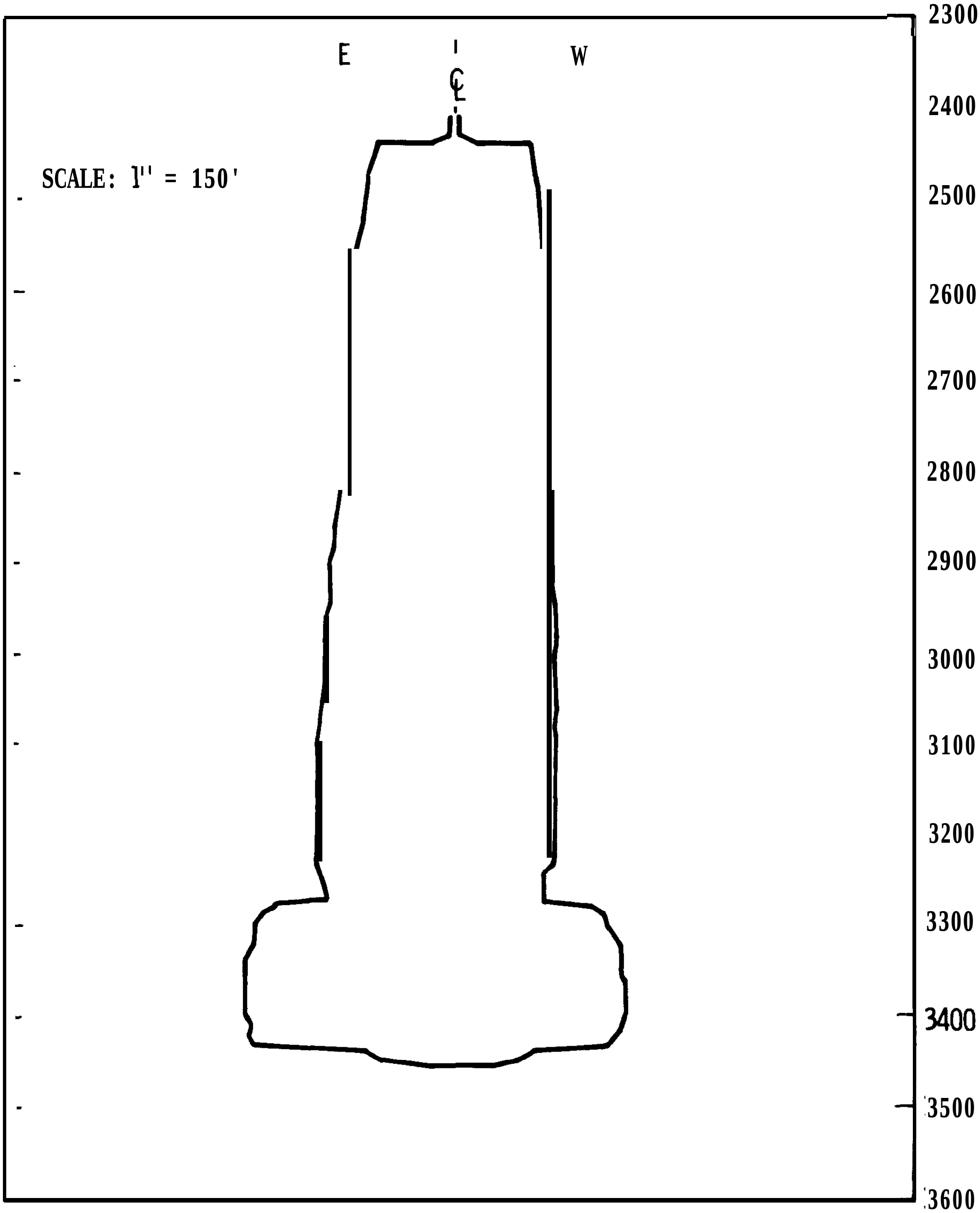

Figure 4.
WEST HACKBERRY CAVERN 8

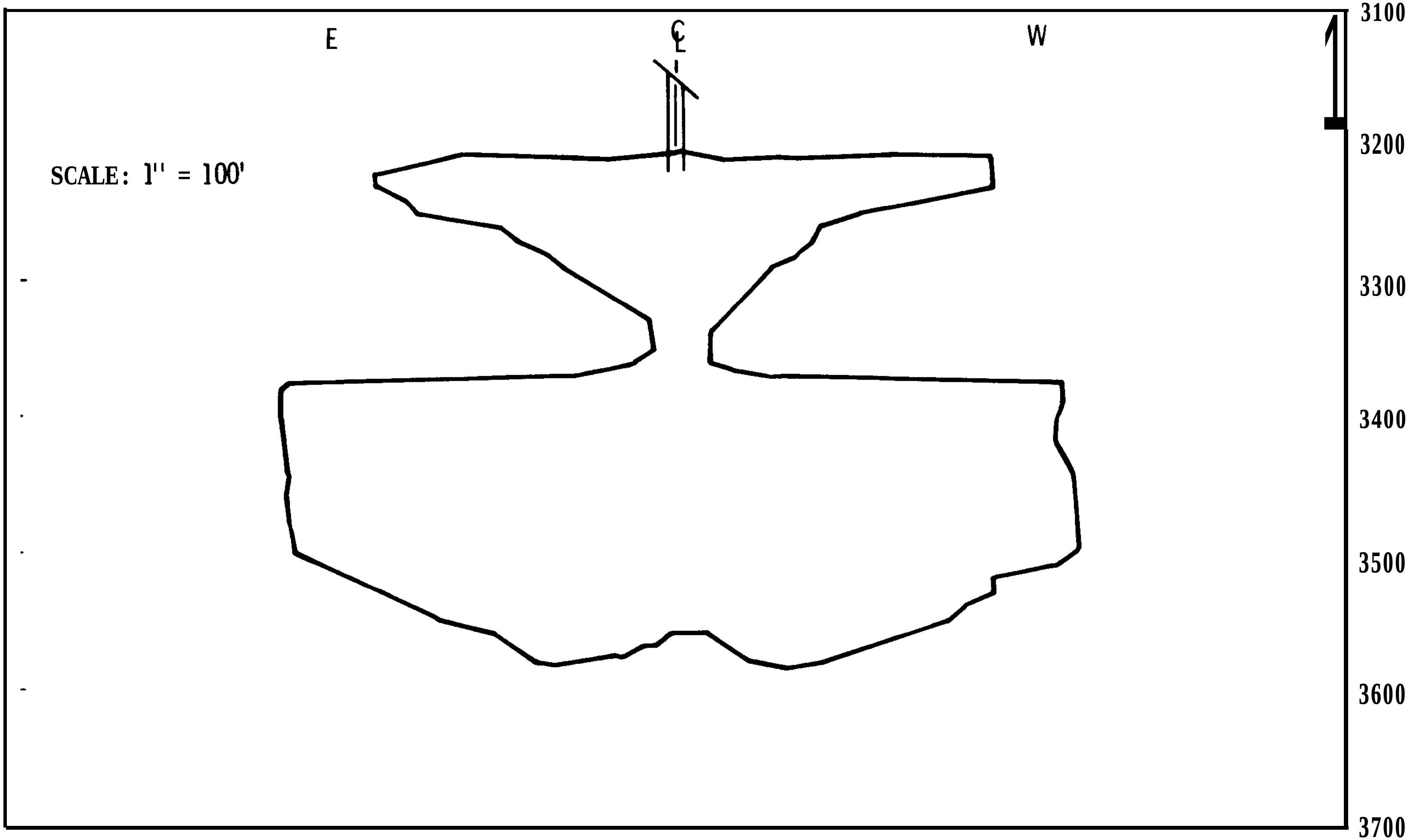

Figure 5.
WEST HACKBERRY CAVERN 9

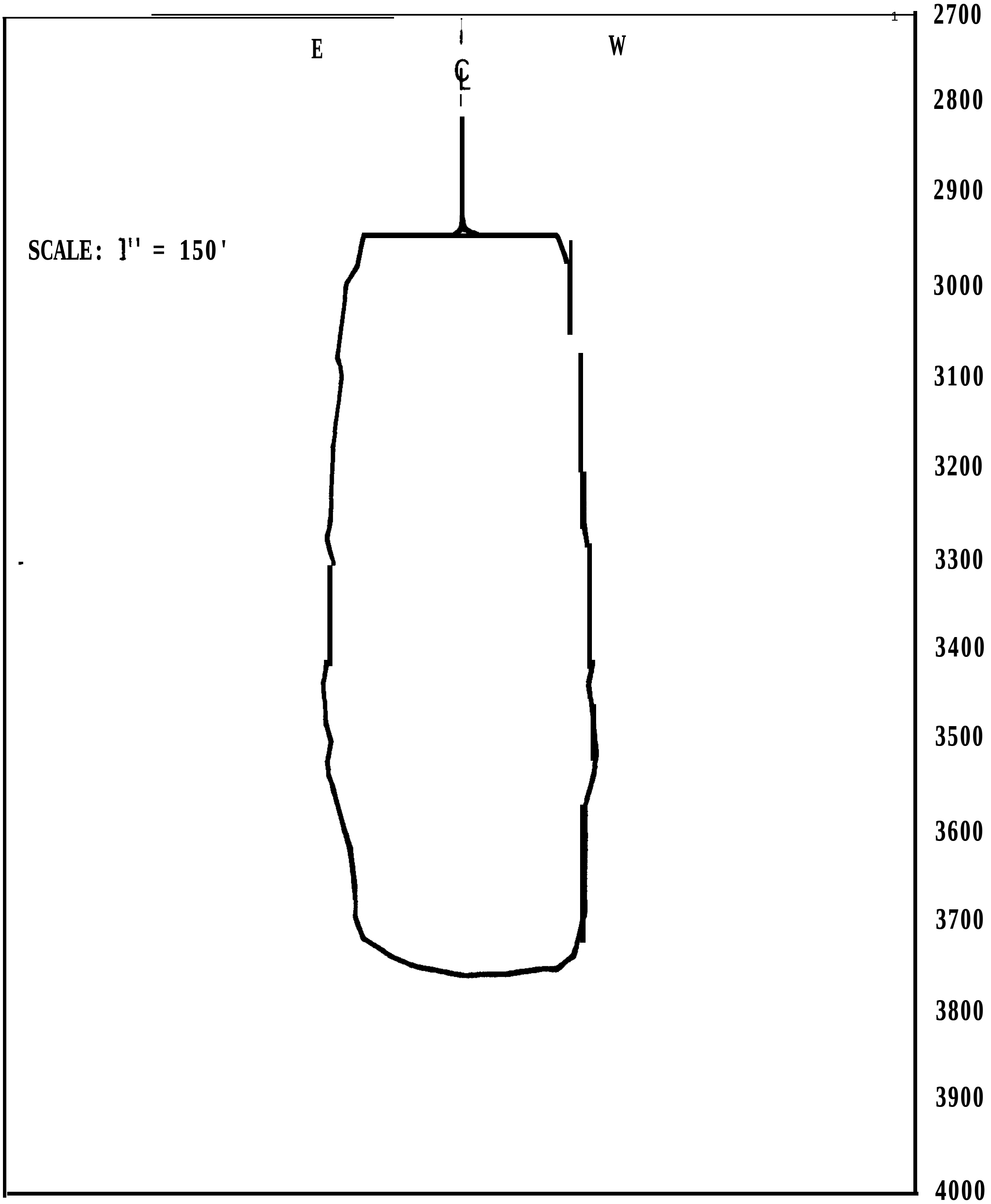

Figure 6.
WEST HACKBERRY CAVERN 11

Phase 1 Report

Geological Site Characterization
Strategic Petroleum Reserve Site
West Hackberry, Louisiana

Prepared for

Sandia National Laboratories
Albuquerque, New Mexico

July 1980

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Appendix Figures

1.0 SUMMARY AND CONCLUSIONS

Phase I geologic and hydrologic characteristics of the West Hackberry SPR Site in southwest Louisiana were compiled and reviewed by Woodward-Clyde Consultants for Sandia National Laboratories as part of the Strategic Petreoleum Reserve (SPR) program of the U.S. Department of Energy.

The successful operation of existing and projected salt dome caverns is dependent on: 1) the presence of massive impermeable salt; 2) the stability of the salt mass; and 3) the geologic conditions conducive to reliable operation of surface facilities. In this regard, the objectives of the study reported herein were:

1) To compile, assess, and review geologic, hydrologic, and geotechnical data that are significant to the site characterization.

2) To analyze and interpret these data and characterize the geology, hydrology, and geometry of the salt dome, cap rock, and overlying surface and near-surface deposits.

3) To identify geologic, hydrologic, and meteorologic conditions that may be hazardous to the West Hackberry SPR Site facility, and to assess whether or not these conditions are present at the site.

4) To identify instrumentation and long-term monitoring requirements of the West Hackberry SPR Site.

The scope of work for this study was limited to the review and analysis of existing data. In some cases, existing data were reinterpreted in order to enhance the understanding of the subsurface structure and geometry of the salt dome in the vicinity of the West Hackberry SPR Site.

1.1 SUMMARY

1.1.1 Regional Geology

The known geologic history of the Gulf Coast region began with early Paleozoic deposition in a major structural trough and late Paleozoic uplift and mountain building. Initial development of the Gulf Coast Geosyncline during the early Mesozoic was accompanied by deposition of the Louann Salt. The Louann Salt serves as the source of the salt for salt domes in the Gulf Coast region, including the West Hackberry dome. The geosynclinal subsidence, which continued through the remainder of the Mesozoic and the entire Cenozoic, resulted in deposition of an extremely thick wedge of elastic sediments overlying the Louann Salt. Within the Gulf Coast Geosyncline, which includes the West Hackberry SPR Site, the principal structural features are salt domes and growth faults. The seismicity of the Gulf Coast region is negligible.

1.1.2 Site Geology and Hydrology

Major piercement by the West Hackberry dome occurred during the late Miocene, and minor dome piercement continued through the Pliocene, Pleistocene, and possibly Holocene. A complex fault pattern over and adjacent to the dome developed concurrently with dome piercement. This pattern has been recognized from analysis and contouring of shallow subsurface stratigraphy- Many faults have been correlated with both surface lineaments and irregularities on top of cap rock and salt. The major structural pattern observed over the dome is a horst and graben complex of faults trending northeast-southwest. Structural irregularities in the cap rock and on top of the salt have induced a through-going fault system that has affected all of the sediments overlying the salt, and perhaps the salt as well.

The age of sediments in the section adjacent to the salt dome ranges from Oligocene to Holocene; over the dome only Pliocene and younger sediments are preserved. Near-surface units at the West Hackberry SPR Site were deposited on the late Pleistocene Prairie surface that was cut on older Pleistocene marine silts and sands. The site is veneered by Holocene coastal marshland deposits. The soil at the site consists of collapsible eolian silt and sandy silt, underlain by desiccated clay, with some sand and silt of the Prairie Formation.

The West Hackberry SPR Site vicinity is characterized by flat, low wetlands, except for the elevated area overlying the West Hackberry salt dome. Subsidence has occurred around the dome, exemplified by the increase in the size of Black Lake. This subsidence parallels the trend of hydrocarbon production. The primary surface-water features in the vicinity of the site are the southern portion of the Calcasieu River basin and the marshland dotted by several lakes, the largest being Calcasieu Lake and Black Lake.

The loo-yea flood level at the site is the result of hurricane storm-surge, and is not generated by a fluvial overflow. The magnitude of the predicted loo-year storm-surge at the site is currently calculated at 4.5 feet.

The principal source of ground water in southwestern Louisiana is the Chicot aquifer, which is present over and adjacent to the West Hackberry salt dome. Locally and regionally, the aquifer consists of three sand units. Recharge is from a variety of source areas. The potentiometric surface of these sands declines to the north, as a result of large historical pumping in the Lake Charles area. High concentrations of methane are released with water from water wells in the site vicinity.

1.1.3 Geology of Cap Rock

Cap rock is present in direct contact with the salt over most of the West Hackberry dome. The thickness of the cap rock ranges from zero at the edges of the salt to a maximum of 550 feet in the southwest corner of Section 20. The cap rock surface ranges in elevation from -1,500 feet at the top of the dome to about -2,700 feet on the flanks. In plan view, the cap rock is elliptical in shape.

The cap rock consists of an upper zone of dolomite and anhydrite, which is underlain by up to 150 to 200 feet of anhydrite and halite. Some cavities have been identified in the upper cap rock, but additional geologic and hydrologic information is needed to better define the cap rock.

1.1.4 Geology of the Salt

The West Hackberry dome is part of a salt ridge that includes both the East and West Hackberry domes. The top of the salt is at a maximum elevation of approximately -2,000 feet. In plan view, the dome has an elliptical shape, with a major reentry along the minor axis of the ellipse. Structural irregularities on the top of the salt closely correspond to faults identified in overlying sediments. The geometry of the dome suggests that it is comprised of at least two spines separated by a boundary shear zone. An external shear zone, consisting of gouge or heaving shale, separates the interior salt mass from surrounding sediments.

Although available data on the composition of the salt at West Hackberry are limited, they do indicate that the salt consists principally of medium to coarsely crystalline halite and about 3 percent local anhydrite inclusions. No fluid or sediment inclusions have been reported in the salt at the West Hack-berry dome.

1.1.5 Hazards

Geologic hazards that may affect the design, operation, or abandonment of the SPR facilities; the safety of personnel: or the site environment are comprised of natural hazards, design-construction-operations hazards, and man-induced hazards.

Of the natural hazards (earthquakes, natural subsidence, hurricane-induced flooding, and non-tectonic fault displacement), only hurricane-induced flooding and fault displacement are expected to have an impact on SPR operations. The impact would not be on the long-term operation of the facility, but on day-to-day operations and facility maintenance. Displacement of non-tectonic faults may affect surface facilities situated on top of a fault and subsurface facilities transected by a fault.

Possible design-construction-operations hazards may be related to composition and integrity of sediments, cap rock, and salt. These hazards can adversely affect SPR operations, such as risk to facilities from collapsible soils; risk to stability and integrity of caverns in salt due to cavernous conditions; loss of cement in cavernous cap rock; leakage due to possible high porosity and permeability of shear zones; explosive threat from accumulation of methane gas; and potential corrosion of well casing, cement plugs, and other down-hole material due to hydrogen sulfide in cap rock.

Man-induced hazards that may adversely affect the West Hackberry SPR Site include gas release of stored petroleum products and fluid-withdrawal subsidence, which would increase the exposure to flooding hazard, cavern collapse, and cavern closure.

1.2 CONCLUSIONS

1) The data available to evaluate the subsurface geologic and hydrologic conditions at the West Hackberry SPR Site are incomplete. The general conditions at the site can be characterized; however, local variations, such as the lithology and integrity of the cap rock and salt mass in the area of cavern placement and the structure and geometry of the dome along the north flank where new caverns are planned, are uncertain. To increase the confidence in the characterization of the geometry, lithology, structure, and hydrology of the salt mass and cap rock, additional data are required.

2) Subsidence has been recognized in the area around West Hackberry dome. There is presently an absence of leveling control to either establish the exact elevation at the West Hackberry SPR Site facility or to monitor the extent and rate of subsidence.

Three types of subsidence could impact the West Hackberry SPR Site facility: natural subsidence, subsidence related to fluid withdrawal, and surface collapse. Natural subsidence at the site related to differential uplift over the dome, and/or subsidence of areas surrounding the dome, should only amount to an estimated several inches in 100 years. Fluid withdrawal from continued petroleum production off the dome, and groundwater exploitation over the dome, could result in an estimated several or more feet of subsidence at the site in 100 years. The potential for collapse of sediments into abandoned caverns is uncertain.

3) The current loo-year storm-surge projection of 4.5 feet is questionable. The methods used to derive the current

projection are outdated; documentation of the calculations for the surge projection is lacking. Comparison of the surge projection at West Hackberry to the adjacent Sabine Lake area to the west suggests the storm-surge projections for West Hackberry may be significantly low (as much as 4 feet).

4) Non-tectonic faults associated with salt dome emplacement underlie and, in some cases, project to the surface at the West Hackberry SPR Site. Some of these faults appear to displace surficial sediments. Displacement due to the natural progression of dome growth on faults identified at the site is expected to be less than 6 inches during the operating life of the SPR program. Potential displacements across these faults due to differential subsidence could be several feet. The potential for and amounts of these possible displacements are uncertain. The likelihood of potentially damaging earthquakes associated with these faults is extremely low.

5) High concentrations of entrained methane have been identified in ground water from aquifers overlying and adjacent to the West Hackberry dome. Explosions could result from the buildup of this gas if proper and adequate venting procedures are not followed in pumping and storage of the water.

6) No procedures for retirement of the caverns from operation have been identified.

2.0 INTRODUCTION

Sandia National Laboratories has been given the responsibility for the geotechnical portion of the Strategic Petroleum Reserve (SPR) program of the Department of Energy (DOE). Part of the program includes a geologic site characterization of selected petroleum storage sites in the Gulf Coast region. This report presents the results of the Phase I geologic site characterization investigations of the West Hackberry salt dome. The West Hackberry SPR Site is located in Cameron Parish, about 3 miles west of Hackberry, Louisiana (Figure 2.1). (The term "site," as used in this report, refers to the actual area that is owned and operated by DOE for the storage of petroleum products.)

2.1 PURPOSE AND OBJECTIVES

In general, the primary purpose of this investigation was to review the site geologic and hydrologic conditions and to describe these in a characterization report that can be used by DOE, Sandia, and other SPR contractors in the planning, design, construction, operation, and abandonment of the SPR site. Topics for which additional data are required to complete the site characterization were identified. In specific, the objectives of the investigation are:

1) To compile, assess, and review geologic, hydrologic, and geotechnical data that are significant to the site characterization.

2) To analyze and interpret these available data and to characterize the geology, hydrology, and geometry of the salt dome, cap rock, and overlying surface and near-surface deposits.

3) To identify geologic, hydrologic, and meteorologic conditions that may be hazardous to a SPR facility and to assess whether or not these conditions are present at the West Hackberry site.

4) To develop an understanding of the instrumentation and long-term monitoring requirements of the West Hackberry SPR Site, based on the local geologic conditions and the planned geometry of the storage chambers.

2.2 SCOPE OF WORK

The scope of work for the Phase I site characterization investigation is, in general, limited to the review and analysis of existing data. As appropriate, new interpretations were made of existing data in order to better characterize subsurface structure and geometry.

To achieve the objectives outlined above, the investigation was divided into a series of tasks and subtasks. The tasks are:

Task 1 - Acquisition, Evaluation, Interpretation of Data

The purpose of this task was to acquire, compile, evaluate, and interpret existing geotechnical data pertaining to the West Hackberry SPR Site. All data pertinent to the SPR project were identified and the quantity and quality of available data to develop a site characterization were evaluated. In addition to site-specific and regional data, generic data on salt dome emplacement, exploitation, and cap rock formation were reviewed. This task was divided into three subtasks consisting of data acquisition, data evaluation, and data interpretation.

Task 2 - Characterization of Surface Geology and Hydrology

The purpose of this task was to characterize the surface and near-surface geologic and hydrologic conditions at the West Hackberry SPR Site and to identify the impacts of these factors on the SPR site facilities. The task was divided into four subtasks consisting of regional geologic characterization, site geologic characterization, surface hydrologic characterization, and ground-water characterization.

Task 3 - Geologic, Hydrologic, and Geophysical Characterization of Cap Rock

The purpose of this task was to characterize the cap rock environment at the West Hackberry SPR Site. The task was divided into four subtasks consisting of definition of cap rock geometry, characterization of cap rock materials, analysis of the hydrology and chemistry of cap rock fluids, and evaluation of effects of man's activities on cap rock condition and stability.

Task 4 - Characterization of the Salt Dome

The purpose of this task was to define the geometry of the salt dome and characterize the internal structure and composition of the salt mass. The task was divided into three subtasks consisting of an evaluation of the history of drilling and mining activities that have penetrated the salt, definition of the boundaries of the salt mass, and characterization of the internal lithology and structure of the salt.

Task 5 - Assessment of Natural Hazards

The purpose of this task was to assess the natural hazards that might affect the site and to assess their influence on the site. The hazards that were considered included seismicity of tectonic origin or possibly induced by the petroleum reservoir around the dome; faulting that may be associated with local uplift or with subsidence of the dome relative to the surrounding sediments and possible regional growth faults; and the effects of hurricanes, floods, or similar events.

Task 6 - Planning Phase II Characterization Studies

During Phase II of the site characterization studies, additional data will be acquired through instrumentation, drilling, material testing, etc. to complete the site characterization. The purpose of this Phase I task is to assess if and to what extent a Phase II effort will be required. Design concerns that evolved during the course of this Phase I study required an accelerated schedule so that an initial Phase II geophysical survey was implemented concurrently with the characterization study. The results of this geophysical work will be presented in a separate report.

Task 7 - Planning for Long-Term Monitoring

Phase I site characterization studies identified key geotechnical parameters to be monitored during long-term operations. Monitoring techniques and instrumentation of other critical facilities were reviewed for possible application to the SPR site. Specific instrumentation for monitoring fault creep, subsidence, changes in cavity dimensions, salt flow, well alignments, ground-water chemistry, cavity pressures and temperatures, and other critical parameters were investigated. New instrumentation and monitoring techniques will be identified for further development as required.

During the Phase I study, two tasks were added %;3 the characterization studies. The first of these, special surveying studies, was initiated because existing surveys of the site and surrounding vicinity were inconsistent and because accurately locating existing wells and test holes in the site vicinity was impossible. The second additional task, core logging, was undertaken to provide additional site-specific data on composition of salt, cap rock, and overlying sediments at West Hackberry and two other SPR sites from cores collected during the SPR program.

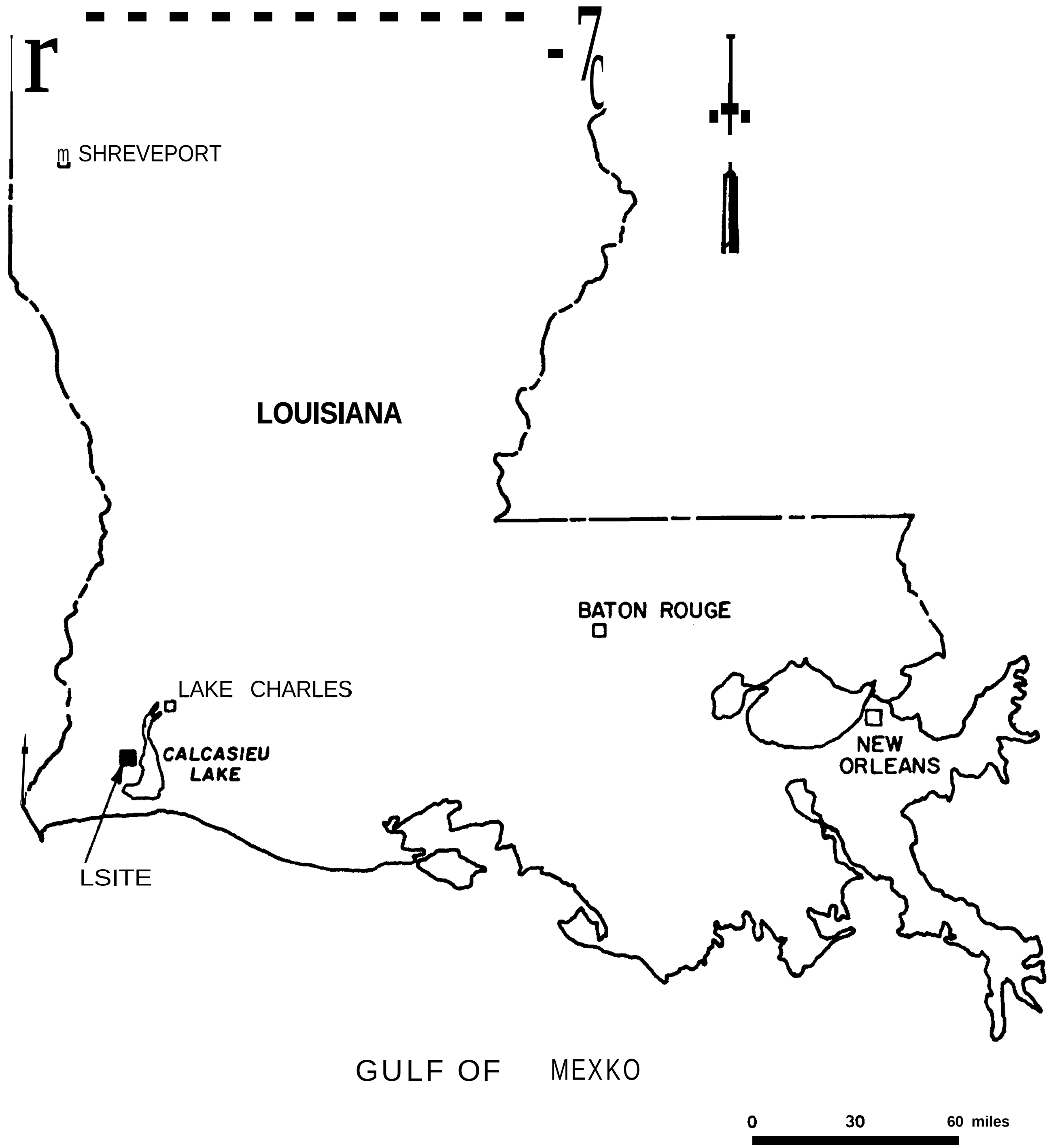


figure 2.1
LOCATION MAP OF THE WEST HACKBERRY SPR SITE

3.0 REGIONAL GEOLOGY AND SEISMICITY

3.1 PHYSIOGRAPHY

The West Hackberry site lies within the West Gulf Coastal Plain physiographic region[22]. Four depositional surfaces are recognized in southwestern Louisiana (Figure 3.1): three of the surfaces developed during Pleistocene interglacial stages; the fourth surface is Holocene-age and evolved by sedimentation during the current high sea-level stage of the past 5,000 years.

Inland from the coast, the depositional surfaces increase in both age and elevation. The elevation of the oldest plain in southern Louisiana, the Bentley surface, ranges from 100 to 200 feet. The elevation of the Montgomery surface ranges from 70 to over 125 feet, and the elevation of the Prairie ranges from between 70 to 100 feet to near sea level. Each progressively older Pleistocene plain crops out farther inland and dips seaward under the sediments that form the next younger plain. This is due to a net inland uplift and/or coastal subsidence during Quaternary time; thus, each younger and seaward Pleistocene plain slopes seaward at progressively smaller rates.

The West Hackberry site is situated on an older Pleistocene (Prairie) depositional surface that has a veneer of Holocene coastal marshland deposits.

3.1.1 The Prairie Plain

The northern portion of the general site vicinity, that part in Calcasieu Parish and the northern limits of the Cameron Parish (Figure 3.1), is within the Prairie Plain. This depositional surface is composed of sediments that correlate with the Beaumont Formation of Texas. The slope of the Prairie is very gentle toward the Gulf of Mexico, ranging from l-l/2 to 2 feet per mile. Because of this gentle slope, the Prairie reaches a maximum elevation of only 100 feet in its northernmost exposures in Louisianasl. The Prairie surface forms slight, almost imperceptible relief, except along the principal streams. Micro-relief on the Prairie surface reflects abandoned channels, oxbows, natural levees, and flood basins of the ancestral Red River.

3.1.2 Coastal Marshland

The coastal marshland, which comprises a veneer over the southern portion of the study are,a, is a region of extremely low relief. The only change in the topography are domal structures, such as West Hackberry, and isolated cheniers (old beach ridges). The cheniers are composed of sand and shell that were deposited by wind and waves during stormssl. The cheniers are, in general, fairly narrow topographic features, elongated parallel to the coastline. Their slope is steep on the seaward side and gentle on the inland side. This asymmetrical shape is produced by the wave wash-up on the Gulf side and the deposition of materials by wave spill-over down the back slope. The marshland itself is covered mainly by water grasses and, only in a few places, rises more than 5 feet above sea level. Meandering tidal channels and lakes are common.

3.2 GEOLOGIC HISTORY

The major sedimentary and tectonic events in the Gulf Coast region from Paleozoic through Cenozoic time are summarized in Table 3.1. The following sections briefly outline the geologic development of the southwestern Louisiana area from the Paleozoic era to the present.

3.2.1 Paleozoic Era

In Louisiana, the geologic history of the Paleozoic era can be postulated only by studying rock exposures in the Ouachita Mountains of Oklahoma, in the Llano Uplift of central Texas, and in the Marathon area of west Texas (Figure 3.2). These data have been augmented by study of rock cores from wells drilled along and near the Ouachita Tectonic Belt.

During most of the lower and middle Paleozoic era, the seas in the Gulf region were epicontinental, and carbonate sedimentation predominated. The Ouachita Geosyncline (a large elongated structural trough) was a sinuous, long, relatively narrow trough during the lower Paleozoic (Upper Cambrian). The main structural development took place during the middle Paleozoic. The Ouachita Geosyncline subsequently was destroyed during the Pennsylvanian Ouachita orogeny (mountain-building process).

The late Paleozoic was characterized by transgressive seas when carbonate and elastic materials were deposited. A regression began at the end of the era, and thick sequences of evaporites were deposited. At the end of the Paleozoic, the seas withdrew from the Gulf Coast region, and the area was subjected to uplift and erosion.

3.2.2 Mesozoic Era

During the early and middle Mesozoic, the Gulf Coast region was chiefly a landmass undergoing erosion. Triassic sediments are found in Texas along the Cap Rock escarpment and in the Amarillo area, as well as in northeastern Texas and southern Arkansas. The sea that covered the area was confined to a fairly small basin, the axis of which passed westward from Cuba toward Mexico. During Early Jurassic times, the continental edge was depressed and tilted southward toward the sea, initiating the development of the Gulf Coast Geosyncline as a continuously subsiding basin. Transgression of the sea began, and, as the sea remained fairly shallow, evaporitic environments were created. The combination of the prevailing arid climate and deposition rates equal to the basin subsidence rate created thick accumulations of evaporites, chiefly halite and anhydrite. Subsidence and transgression continued until the end of the Cretaceous, when the seas withdrew from the Gulf Coast region.

3.2.3 Cenozoic Era

Great thicknesses of sediments, estimated at about 50,000 feet3', accumulated in the Gulf Coast Geosyncline during the Cenozoic era. These deposits are part of the great geosynclinal sedimentary complex of continental, deltaic, and marine deposits. They accumulated as overlapping, irregularly lenticular sedimentary masses; their axes of maximum deposition (depoaxes) are approximately parallel to the modern shoreline". Marine strata accumulated around the seaward edges of the individual deltaic masses, whereas marginal and fluvial sediments were deposited landward from the depoaxes.

The Cenozoic era was characterized by alternating stages of regressive and transgressive seas, but the depoaxes gradually migrated gulfward as the seas continued to regress and shift, together with the coastline, towards the south. During the Quaternary, regressions and transgressions were generally related to glacial and interglacial episodes. In general, episodes of rising sea level and high sea level stands are periods of deposition, and intervals of falling sea level and low sea level stands are periods of erosion and valley downcutting.

3.3 STRATIGRAPHY

A general time-stratigraphic column and the geologic history of the area are shown in Table 3.1. The following discussion of stratigraphic units is limited to the Louann Salt and younger formations.

3.3.1 Mesozoic Deposits

Despite some suggestion of Permian accumulation, the prevailing consensus among Gulf Coast geologists is that the Louann Salt is Upper Triassic-Lower Jurassic in age[32]. This age was based upon an evaluation of spores (microfloral fossils) found in some salt cores and salt mines in Texas and Louisiana. Upper Triassic fossil plants (*Macrotaeniopteris magnifolia*) were found in the Eagle Mills Formation of Arkansas, which immediately underlies the Louann Salt[105].

Total thickness of the salt varies and is not known with certainty: however, salt thickness is estimated to be between 1,000 and 5,000 feet. Anhydrite beds are found throughout the Gulf Coast Geosyncline associated with the salt. Some areas of the Gulf Coast Geosyncline are thought to be free of salt, such as the Sabine Uplift and the San Marcos Arch (Figure 3.2). It is believed that these areas represent either topographic highs at the time of salt deposition or displacement of salt after deposition by lateral flowage caused by the weight of overlying rocks. Other rocks of Jurassic age in northeastern Texas consist of elastic sediments and limestone.

The Cretaceous rocks in the Gulf Coast area are commonly subdivided into the Comanche (Comanchean) and Gulf (Gulfian) series, terms which are used in a general way to describe the Lower and the Upper Cretaceous rocks, respectively. These rocks crop out in southern Arkansas and northern Texas. Their combined thickness is estimated to be around 9,600 feet.

The Comanchean Series consists of carbonate rocks, chiefly limestone, and minor shale and sandstone. Near the end of the period of Comanchean deposition, igneous rocks were intruded into the sediments as isolated stocks along a band corresponding to the Ouachita Tectonic Belt. The Gulfian Series is composed mostly of elastic sediments, again with some igneous stocks of basaltic composition injected generally along the same tectonic belt.

3.3.2 Cenozoic Deposits

Cenozoic sediments are exposed throughout Louisiana (Figure 3.3). In the southern part of the state, Quaternary sediments are mapped at the surface, and in the northern part, Tertiary sediments are mapped at the surface. The Tertiary units are part of an arcuate band that extends from southern Texas into Mississippi, southern Alabama, and northern Florida.

Tertiary

The Tertiary period was marked by an accumulation of a great thickness of continental, deltaic, and marine deposits of the Gulf Coast Geosyncline. Sediments deposited in southwestern Louisiana during the Tertiary include approximately 4,800 feet in the Paleocene and Eocene, 4,800 feet in the Oligocene, 16,000 feet in the Miocene, and 12,000 feet in the Pliocene.

The base of the sequence, known as the Midway Group, is composed mainly of clays that were deposited in transgressive seas during the Paleocene. Overlying the Midway, and deposited during early Eocene, is the Wilcox Group, which consists of near-shore, lacustrine and lagunal clays, silts, and fluvial sands. These sediments were deposited in regressive seas. As a consequence of the continued transgressions and regressions, similar sedimentation patterns continued through the rest of the Eocene. The Claiborne Group, consisting of sands, clay, silt, and some interbedded limestone, was deposited on top of the Wilcox. Overlying the Claiborne Group are sands and clays of the Jackson Group.

The upper Eocene Jackson Group is overlain by Oligocene sediments of the Frio and Anahuac formations. Within southwestern Louisiana, the Hackberry facies is present in the middle Frio section. The Frio generally grades from sandstone to shale in the subsurface towards the Gulf. The Hackberry facies, which is a fauna1 stratigraphic section identified in the coastwise downdip Frio, consists of a lower sandy zone and upper shale section. The Anahuac Formation is chiefly sandstone in the updip section but grades to a thick shale sequence and a few sandstone or limestone beds. However, one calcareous section, the base of the Hetereostagina zone, is a persistent marker used for regional mapping in the Gulf Coast.

The Miocene-age units of Louisiana are subdivided into the Catahoula and Fleming formations for surface outcrops but are generally referenced as lower, middle, and upper Miocene in the subsurface. The Miocene sediments are chiefly of deltaic origin, deposited during regressive seas, broken by minor transgressions.

During the Pliocene, a sequence of fine- to medium-grained sands, interbedded with laminated clays, was deposited. The general lithology of these sediments is similar to that of the underlying Miocene sediments; however, the sand is more lignitic, the clay is less calcareous, and the proportion of sand is generally greater[51].

Quaternary

The Pleistocene units of the Louisiana Gulf Coast are, from oldest to youngest, the Williana, Bentley, Montgomery, and Prairie formations. Thicknesses of the Pleistocene deposits exceed 2,000 feet[104]; however, overlying Holocene deposits are a maximum of 300 feet thick[51] in the Atchafalaya Basin but rarely exceed 30 feet to the west in the vicinity of the Hackberry dome.

The Williana consists of a basal gravelly sand that is overlain by sand and minor clay. The Bentley and the Montgomery formations are sands interbedded with clay and contain some cherty gravel. The Prairie Formation is similar in composition, but the sediments occur mostly in lenticular layers of sand and clay.

Holocene sediments consist of sands, silts, clays, and some gravels deposited by streams on alluvial and deltaic plains and by wind and wave action along the shoreline of the Gulf of Mexico, where they form barrier islands and bars. Holocene-age sediments are also accumulating in coastal lagoons, bays, and marshes and form the alluvial floors of the valleys of modern streams for long distances inland.

3.4 STRUCTURAL GEOLOGY

The salient regional tectonic features located within 200 miles of the West Hackberry site are: the Gulf Coast Geosyncline, the Sabine Uplift, the Monroe Uplift, the LaSalle Arch, and the Mississippi Embayment (Figure 3.2). Other structural features of regional significance are growth faults, salt domes, and related structures. Growth faults are discussed in this section. Salt-related structures are discussed in Section 6.

3.4.1 Reaional Tectonic Features

Monroe and Sabine Uplifts - The Monroe and Sabine uplifts developed during Mesozoic-Cenozoic times, probably associated with isostatic readjustment due to the elevation changes of large landmasses. Roth of these uplifts are relatively flat-topped structures that were already topographic highs at the beginning of the Mesozoicgo. Some of the irregularities in the shape of these structures are associated with igneous intrusionsgo. Salt structures are not known to occur on these uplifts.

LaSalle Arch - The LaSalle Arch is a gentle anticlinal structure trending northwest-southeast. Apparently, only rocks of Cenozoic age are affected by the arch". The arch presumably resulted from the development of the Gulf Coast Geosyncline and the associated regional isostatic readjustment.

Mississippi Embayment - The Mississippi Embayment is a broad, elongate structural depression over 350 miles long that plunges gently toward the Gulf. The course of the Mississippi River closely follows the embayment. South of the Monroe Uplift, the embayment merges into the Gulf Coast Geosyncline. Late Cretaceous (Gulfian) seas first invaded the embayment and sedimentation continued through Eocene timego.

Gulf Coast Geosyncline - The Gulf Coast Geosyncline is a long, broad area of regional subsidence that appears to be isostatically controlled. Several thousand feet of Mesozoic and as much as 50,000 feet of Cenozoic sediments have been deposited in the geosyncline. The geosyncline extends from northwestern Florida to northeastern Mexico for a distance of about 900 miles and extends as much as 500 miles inland (Figure 3.2). This geosyncline has controlled, in a direct or indirect manner, the development of other Mesozoic and

Cenozoic structures of the Gulf Coast. The geologic history of the Gulf Coast Geosyncline is outlined below.

From Middle Jurassic to Early Cretaceous time, the region surrounding the Louann Salt Basin emerged and the enclosed sedimentary basin became more and more restricted. During the Middle and Late Cretaceous, the seas began to advance and inundated the region, temporarily arresting the development of the geosyncline. Igneous activity also took place during this period.

At the onset of the Tertiary, subsidence and the accumulation of the thick sedimentary sequence was renewed at a higher rate. Periods of transgression (when sedimentation prevailed) alternated with periods of regression (when erosion took place). These variations in sea level produced a series of sediments characterized by the following cyclical depositional environments: fluvial-transitional-coastal-neritic (up to 600 feet deep)-coastal-transitional-fluvial-etc. Concurrently with sedimentation, the position of the coastline, together with the depoaxes, migrated to the south (gulf-ward). Consequently, the age of the rocks cropping out in the Gulf region decreases toward the coast. Growth faults and salt intrusions that affected the coastal and marine areas of the Gulf Coast were formed during the Cenozoic.

3.4.2 Faults

A complex mosaic of variously oriented faults and fault zones breaks the Cenozoic sediments of the Gulf Coast region. For example, in the Texas Gulf Coast alone, more than 7,000 miles of lineaments on aerial photographs suggest that most of these represent faults[52].

Two principal varieties of faults, most of which are normal faults, are recognized in the Gulf Coast region. Many of the faults are regional in extent and are termed "contemporaneous" or Wgrowth" faults. In addition, the intrusion of salt masses is commonly associated with faulting, as discussed in Section 6.

Growth faults are non-tectonic fractures that develop contemporaneously with deposition. A model has been postulated that growth faulting in the Gulf Coast region results from slumping along the trend of large flexures, particularly in post-Eocene beds3'. As the geosyncline subsided gulf-ward, the dip of the depositional surface increased and this increased the tendency for gulf-ward slumping of the sediments. The water-saturated, unconsolidated sediments slumped directly downdip, creating growth faults along the trend of the dip change. A second, modified model postulates that growth faults are initiated by continued deposition, differential compaction, and downwarping of the section (Figure 3.4). The principal mechanisms of this process are differential compaction and gravity sliding8.

The following is a listing of growth fault characteristics6,7,8,10,33,39,94,102:

- Stratigraphic units on the downthrown side of growth faults are thicker than correlative units on the upthrown side (Figure 3.4).

- Most of the growth faults in the Texas and Louisiana Gulf Coast are normal faults and are non-tectonic. In the majority of cases, the downthrown block is down-to-coast (gulf-ward).

- The plane along which slippage occurs tends to flatten at depth, resulting in a curved profile (Figure 3.4). Dips range from 35 to 65 degrees or more.

- The amount of displacement on growth faults is variable along strike and along dip. Characteristically, displacement increases downward and, in some faults, terminates in both the upward and downward directions. Displacement varies from 0 to more than 6,000 feet. Age of faulting appears to bear no relationship to amount of displacement.

- A common characteristic of growth faults is the "reverse drag" (rollover-downbending) in the beds on the downthrown side. This is a phenomenon in which beds on the downthrown side of the growth faults dip into the fault plane rather than away from it (Figure 3.4). This reverse drag is apparently attributable to the flexuring of beds into the "pull-apart" gap created in the upper part of a growth fault that flattens with depth. Secondary faults dipping in the opposite direction to the master fault (antithetic faults) are produced when pressure relief occurs by shearing instead of flexuring.

- Over long distances, the surface traces of growth faults tend to be broadly arcuate and roughly parallel to the regional stratigraphic strike.

3.5 SEISMICITY

The Texas and Louisiana portions of the Gulf coastal region, including the West Hackberry site, are characterized by a very low level of exposure to naturally occurring seismic hazards. The largest historical earthquakes have produced only minor damage.

A detailed review of seismicity in that region is presented in the licensing documents for the South Texas Project14J46. These earthquakes are listed on Table 3.2. It is possible that many of the seismic events that occurred during the past several decades were sonic booms. However, because the events were small and only a few seismograph stations are operating in the region, substantial instrumental studies of Gulf Coast seismicity have not been possible. Much of what has been learned about these events is based upon *'felt" reports of seismic shaking and on occasional seisomograph recordings.

The earthquake in Donaldsonville, Louisiana, on October 19, 1930 (located about 145 miles east of the West Hackberry site) produced a maximum epicentral intensity V to VI (Modified Mercalli) and was located by isoseismal data at latitude 30°N and longitude 91OW. The event was felt over an area of 15,000 square miles. The slight damage observed (broken glass, chimney damage, moved furniture) was probably the result of seismic shaking of the underlying unconsolidated deposits.

Based upon the observed intensities and analytical techniques that are appropriate for the central United States, the focal depth has been estimated to be 7 miles or more[46]. The tectonic origin of this earthquake is not known but, because of its focal depth, is presumed to be associated with the deepening of the Gulf Coast Geosyncline.

The earthquake that occurred in Orange, Texas, on October 17, 1952 (Figure 3.1) was reportedly felt at maximum intensity IV (Modified Mercalli) only in the town of Orange on the coast of the Gulf of Mexico. Additional data were not reported for this event and it was not recorded instrumentally. Such limited data make it difficult to further assess this event's characteristics as a possible earthquake. An earthquake of a similar nature occurred in 1959, approximately 22 miles southeast of the site (Figure 3.1). This earthquake also had a maximum intensity of IV (Modified Mercalli).

Ten earthquakes at the Texas-Louisiana border in 1964 were reported at maximum intensity of up to about V (Modified Mercalli) and were recorded instrumentally with magnitudes of up to 4.4[14]. These events, like the 1930 .earthquake, are attributed to stress released by the basement rocks beneath the sedimentary cover; they are at a depth of 4 miles or more. The events reported since 1966 are considered possible sonic booms[14].

The source area of potentially significant earthquakes within the Gulf Coast appears to be the slowly deforming basement beneath the active Quaternary depositional center along the Coast. In this zone, the rock strength is presumed to be high, and the rock volume is sufficient for potentially significant amounts of elastic strain energy to be accumulated and released. However, the level of tectonic stress appears to be very low, and thus, the potential for natural earthquake occurrence exceeding that of the 1930 earthquake is very low.

The properties of the sedimentary materials that overlie the basement rocks and fill in the Gulf Coast Geosyncline are mechanically isolated or segmented by weaker, mobile elements and do not have the capacity to store or transmit significant amounts of strain energy. Rapid deformation of the sedimentary materials may account for occasional, small-magnitude seismic events. Some of these events may be caused by subsidence associated with rapid withdrawal of fluids from shallow or deep reservoirs.

TABLE 3.1
STRATIGRAPHIC COLUMN
GULF REGION - LOUISIANA

ERA	SYSTEM	SERIES	GROUP/ FORMATION	EVENTS / PROCESSES	YEARS AGO x 10^3
CENOZOIC	QUATERNARY	HOLOCENE		ALLUVIAL, DELTAIC, INTERDELTAIC deposition	
				UNCONFORMITY	10
		PLEISTOCENE	Prairie Montgomery Bentley Williana	Alternate deposition ond erosion related to ~loc~al/ interglocml vtages	
				UNCONFORMITY	2,000
	TERTIARY	PLIOCENE		Salt intrusaon continues	12,000
		MIOCENE	Upper Middle Lower		26,000
		OLIGOCENE	Anahuac Frio / HACKBERRY FACIES	Genrol rcgrrsswe decallion wtth minor tronspressava intervolr	37,000
		EOCENE	Jackson Claiborne Wilcox	Sediments of each youn~cr epoch deposlled progressively forther gulf-word an Gulf Coast Geosynclinr.	
		PALEOCENE	Midway	Continued uplift of Gulf rrgion ond beginning of major Terhory regress~e deposition	53,000 65,000
MESOZOIC	UPPER CRETACEOUS	GULFIAN		Uplift, withdrorol of Gulfion $805, erosion Continuing transgression and devel-apmcnt of Gulf Coast Geosyncline Sibsidance of Gulf region ond beginning of Tronsgrrssion Of Gulfion Seas	
	LOWER CRETACEOUS	COMANCHEAN		Uplift, wlthdrowol of Comoncheon seas, erosion Continuing transgression and devel-opment of Gulf Coast Geosyncline Subsidence of Gulf region and beginning of tronsgresstan of Comanchean seas	
				UNCONFORMITY	136,000
	JURASSIC	UPPER		Uplaft and erosion	
		MIDDLE		Probable Inltiol stage of subsidence and beginning of Gulf Coast Geo-syncline. Hohk and onhydritc deposition	
		LOWER	Louann Salt		
				UNCONFORMITY	190,000
	TRIASSIC		?		
				UNCONFORMITY	225,000
PALEOZOIC	PERMIAN		?	Upllft ond erosion	
				UNCONFORMITY	280,000
				Ouachita orogeny; destruction of Ouachita Geosyncline.	570,000

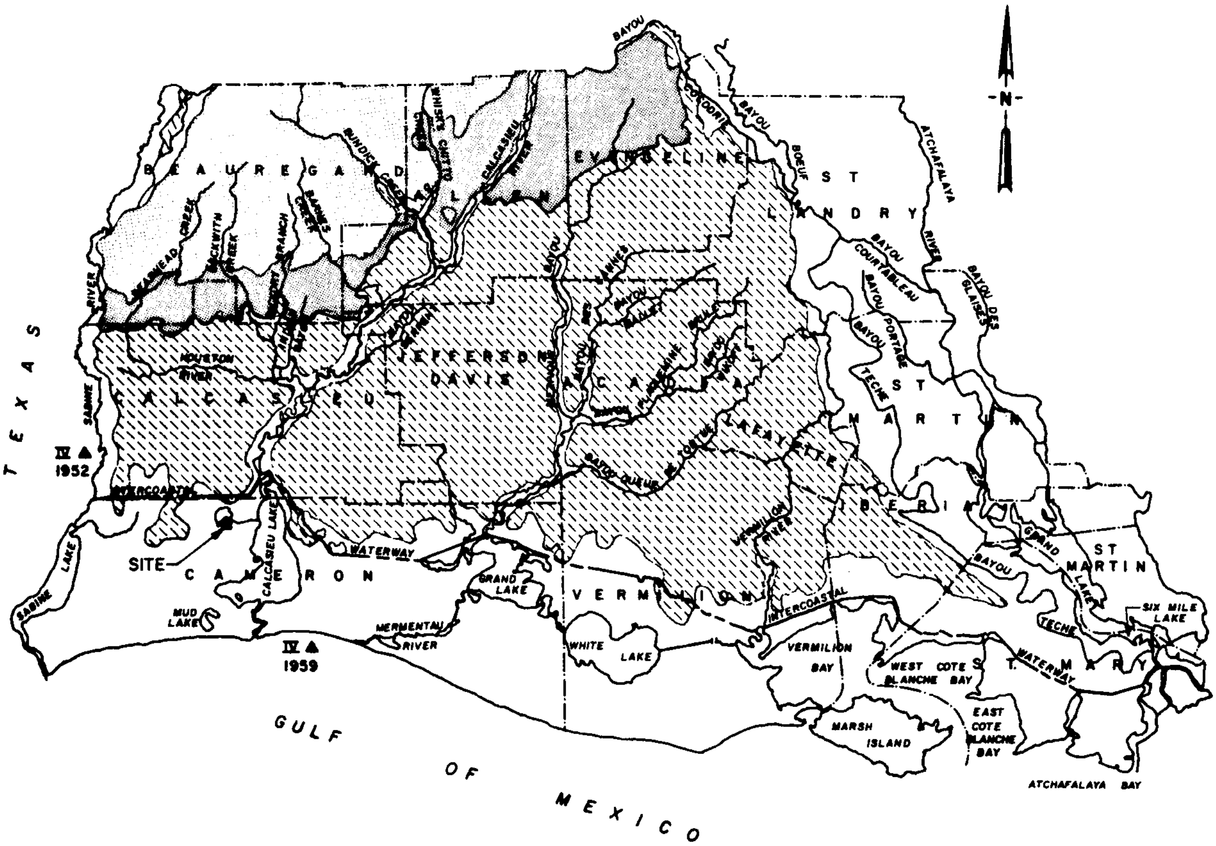
TABLE 3.2

HISTORICAL EARTHQUAKES ALONG THE TEXAS-LOUISIANA GULF COAST
(to 1378)

Date YR-MO-DA	Lat 0'0	Long (W	Intensity m.w*	M=g	Location and Comments
1843 2 14	29.95	90.08			New Orleans
1843 2 15	29.95	90.08			New Orleans
1873 4 30	30.25	97.70	III-IV		Manor, Texas
1882 4 11	29.95	90.08	III		New Orleans
1886 1 22	30.42	92.02			Grand Couteau, Louisiana
1910 5 8	30.13	96.03	IV		Hempstead, Texas
1910 5 11	30.13	96.03	IV		Wallcr and Washington Counties, Texas
1927 12 14	28.95	89.40	IV		Burrwood, Louisiana
1930 10 19	30.00	91.00	V-VI		Donaldsonvllle, Louisiana
1952 10 17	30.12	93.73	IV		Orange, Texas
1956 1 7	29.10	94.80	IV		Galveston Island, Texas
1958 11 19	30.47	91.17	V		Baton Rouge, Louisiana
1959 10 15	29.00	93.10	IV		Creole, Louisiana
1963 11 5	27.40	92.40		4.80	Gulf of Mexico
1964 4 28	31.70	93.60	IV-V	4.40	Western Louisiana; Pineland, Hemphill, and Mllam, Texas (10 events in April-June)
1966 1 15	30.32	93.65	III-IV		Texas-Louisiana Border, Possible Sonic Room
1966 2 1	30.32	93.65	III		Texas-Louisiana Border, Possible Sonic boom
1966 2 2	30.32	93.65	IV-V		Texas-Louisiana Border, Possible Son-it Boom
1966 2 3	30.32	93-65	IV		Texas-Louisiana Border, Possible Sonic Boom
1966 3 24	30.00	94.00			Saline, Texas
1969 6 12	29.70	95.30	I	2.00	Hobby Airport, Houston, Texas; Possible Sonic Boom
1969 6 18	29.70	95.30	I	1.50	Hobby Airport, Houston, Texas; Possible Sonic Boom
1969 6 19	29.70	95.30	I	1.50	Hobby Airport, Houston, Texas; Possible Sonic Boom

*tiodified Mercalli
Source: Woodward-Clyde Consultan~ts, 1980a

Woodward-Clyde Consultants



EXPLANATION

Q GENTLY FORIIATIffl

MONTGOMERY FORMATION

PRAIRIE FORMATION

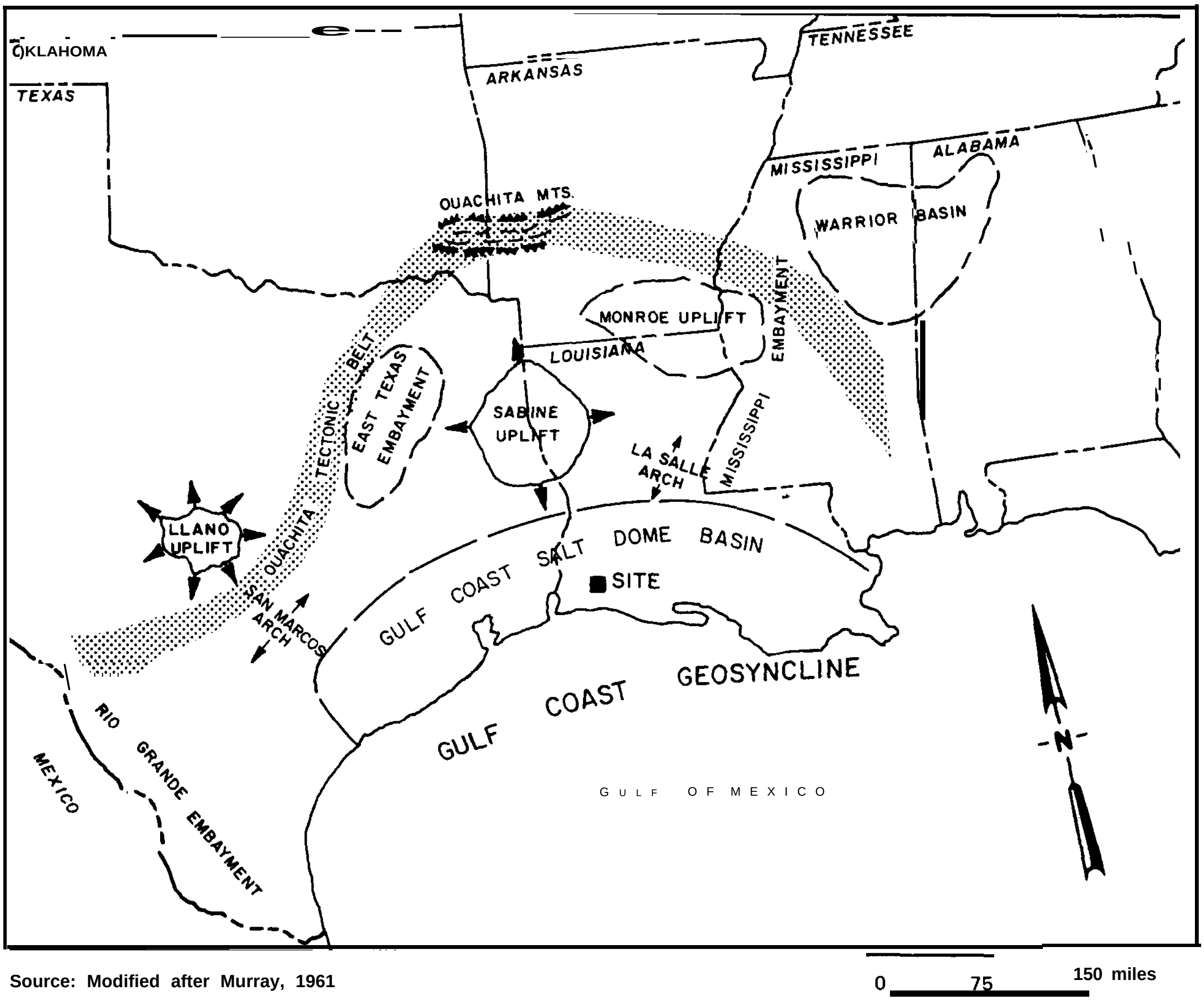
RECENT FLOOD PLAIN AND COASTAL MARSH DEPOSITS

WA EARTHWAKE EPICENTER: ROMAN NUMERAL INDICATES EPICENTRAL INTENSITY GIVEN ON THE MODIFIED MERCALLI SCALE, DATE OF EARTHQUAKE INDICATED.

0 I5 30m1les

Figure 3.1

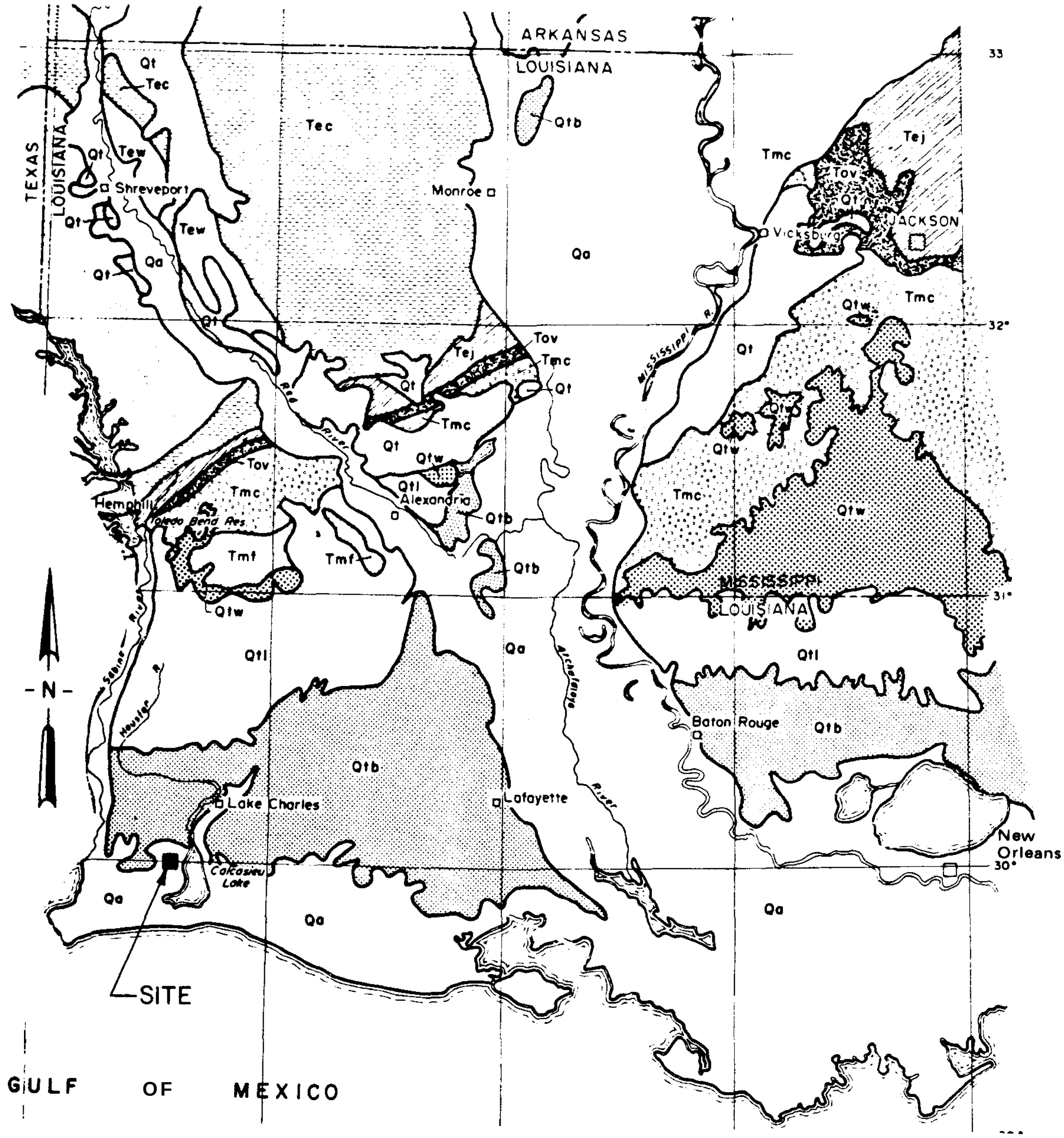
LOCATION MAP, SURFACE DEPOSITS, AND PHYSIOGRAPHIC FEATURES, SOUTHWESTERN LOUISIANA



Source: Modified after Murray, 1961

Figure 3.2

STRUCTURAL ELEMENTS OF THE GULF COAST



Source: Gulf States Utilities Company, 1974

EXPLANATION

SEDIMENTARY ROCKS

CENOZOIC — QUATERNARY — RECENT

- Qa — Alluvium: floodplain deposits

CENOZOIC — QUATERNARY — PLIO-PLEISTOCENE

- Qt — Qt, Fluviatile and deltaic terrace deposits undifferentiated: clays, silts, sand and major gravel
  - Qtb — Qtb, Beaumont Formation, equivalent to Prairie Formation; includes some bar and marsh deposits
  - Qtl — Qtl, Lissie Formation, includes Bentley and Montgomery Formation
  - Qtw — Qtw, Willis (Williana) Formation, equivalent to Citronelle terrace deposits. May be late Pliocene in age.

CENOZOIC — TERTIARY — MIOCENE

- Tmf — Fleming Formation: mostly clay with some silt and sand
- Tmc — Catahoula Formation: tuffaceous, sandy mudstone; lower part coarse quartz sand.

CENOZOIC — TERTIARY — OLIGOCENE

- Tov — Vicksburg Group: dark orgillaceous sediments, partly lignitic and carbonaceous.

CENOZOIC — TERTIARY — EOCENE

- Tej — Jackson Group: glauconitic sands and clays.
- Tec — Claiborne Group: light-colored, fine to medium grained sand; glauconitic marl and gray-brown clay
- Tew — Wilcox Group: mostly silty and sandy clay, with glauconite and lignite.

CENOZOIC — TERTIARY — PALEOCENE

- Tpm — Midway Group: mostly clay, with limy concretions and thin beds of limestone.

MESOZOIC — CRETACEOUS — UPPER CRETACEOUS

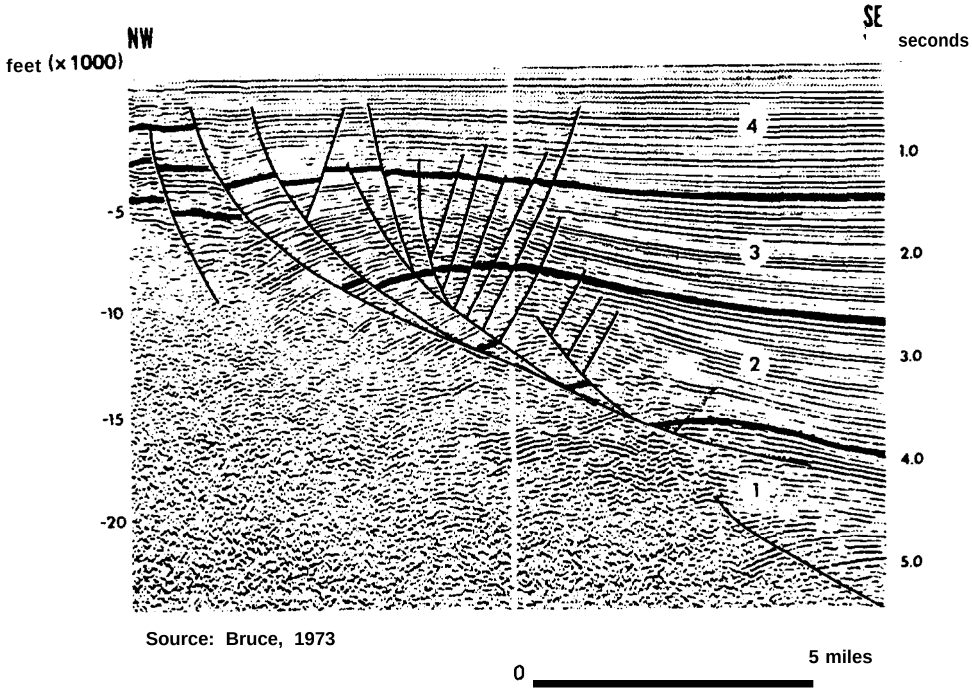
- Ku — Undifferentiated Upper Cretaceous rocks: calcareous rocks dominate; marls, calcareous clays, chalk.

——— Geologic contact

0 30 60 miles

Figure 3.3

GENERALIZED GEOLOGIC MAP OF LOUISIANA



Source: Bruce, 1973

Figure 3.4

SEISMIC ILLUSTRATION OF GROWTH FAULT SYSTEM

4.0 SITE GEOLOGY AND HYDROLOGY

In this section, a general characterization of surface and shallow subsurface geology and hydrology of the West Hackberry SPR Site is presented, including a discussion of site physi- %vw?vr geomorphology, surface soils, shallow subsurface stratigraphy, site structural geology, geologic history of the site, surface hydrology (including flood and storm-surge analysis), and regional and site ground-water hydrology.

4.1 SITE PHYSIOGRAPHY AND GEOMORPHOLOGY

The West Hackberry SPR Site is located about 4 miles south of the boundary of the coastal marshlands and the upland Prairie Plain (Section 3.1 and Figure 3.1). Several lakes are present in the area, the largest of which is Calcasieu Lake, which has an area of approximately 75 square miles. Black Lake, immediately north of the site, had an area of about 4 square miles as shown on aerial photographs (Figures 4.1 and 4.2) and topographic maps dated 1955 (Figure 4.5). At present, Black Lake covers an area between 25 to 50 square miles (Figure 4.3). The increase in the size of the lake is probably due to subsidence.

The site is situated on an elevated area overlying the West Hackberry salt structure. This elevated area, called Hackberry ridge, is about 4.5 miles long and 1.5 miles wide. Elevation of the ridge ranges from 5 to 25 feet above sea level; the marshlands surrounding the dome generally are less than 2 feet above sea level. The West Hackberry SPR Site has elevations ranging from 5 to 20 feet above sea level.

Hackberry ridge is crossed at several places by meandering channels 500 to 1,000 feet wide. These channels may be remnants of Pleistocene river courses. An analysis of aerial photographs and topographic maps of areas that are of elevations greater than 10 feet suggests the presence of an ancient bifurcated distributary mouth bar located south of the dome; this bar may have been part of the Red River Delta or the Mississippi Delta during the late Pleistocene. The location of this distributary channel indicates that by late Pleistocene, the area over the dome was affecting sedimentation as a topographic high.

Other geomorphic features on Hackberry ridge include pimple mounds, scarps, and sag ponds. Pimple mounds are circular mounds of earth approximately 30 to 50 feet in diameter and 1 to 5 feet in height. Pimple mounds are believed to be erosional features that align parallel to slope and follow subdued drainage patterns. They are also aligned parallel to the slope of eroded Quaternary fault scarps. The most abundant and prominent pimple mounds are located on the southern side of the ridge. The locations of pimple mounds appear to reflect Pleistocene and recent drainage patterns.

The locations of young faults in the Gulf Coast region typically are marked by breaks-in-slope or scarps that are in a linear trend on the ground surface and by sag ponds, which form on down-faulted blocks adjacent to faults. Several of these fault-related geomorphic features have been observed at the West Hackberry SPR Site and are discussed in detail in Section 4.4.2.

4.2 GEOLOGIC HISTORY

Major piercement of Cenozoic sediments by the West Hackberry dome most likely occurred during late Miocene time. Southwestern Louisiana was a center of maximum deposition during this period, and dome growth was concomitant with sedimentation. Oligocene and lower to middle Miocene sediments around the West Hackberry dome are consistent in thickness with the same age deposits throughout southwestern Louisiana. Upper Miocene sediments are absent over and immediately around the dome, thus forming an unconformity that is indicative of piercement and either non-deposition or erosion. Unconformities represent a surface of erosion or non-deposition and serve as a record of relative uplift of sediments within a continuously subsiding basin of deposition.

Minor dome piercement continued through the Pliocene, as indicated by the thinning (or absence) of these units over the dome. While gravel is reported nearly as deep as cap rock in some wells, other wells report shales, sands, and gumbo below 500 feet47. The presence of these units is supported by the results of the geophysical log analysis conducted in this study. The deeper clayey sediments probably represent Pliocene deposition and the gravel represents alluvium-filled channels deposited during fluctuations in sea level related to Pleistocene glacial epochs.

The West Hackberry dome piercement continued intermittently through the Pleistocene. The eastern end of Hackberry ridge forms a cliff that is truncated by Calcasieu Lake, exposing a well-developed soil containing many nodules of iron and manganese and underlying "bedrock"[5,47]. (Note: this exposure is no longer readily visible at the described location.) The well-developed soil profile indicates that the surface is mature and probably correlates with the Prairie surface to the north. However, because Hackberry ridge stands topographically higher than the closest exposures of the Prairie surface to the north, it suggests that post-Prairie, late Pleistocene, and possibly Holocene uplift of the dome has occurred.

The presence of a substantial thickness of Pleistocene alluvium is evidence that the dome was not consistently a topographic high and that the area was receiving sediments during much of the Pleistocene. Faulting of Pleistocene sediments indicates that these sediments were present when the late Pleistocene or Holocene uplift occurred.

4.3 SITE STRATIGRAPHY

Information on the subsurface stratigraphy overlying and adjacent to the cap rock and salt dome has been compiled from well logs and published reports. Little data are available on micropaleotology of the sediments, the typical method of age dating, and correlation of subsurface stratigraphy in the Gulf Coast. Consequently, the age of the sediments over the dome is inferred and interpreted rather than derived from data sources. A lithostratigraphic column of the sediments, cap rock, and salt of the West Hackberry SPR Site is shown on Table 4.1.

Holocene sediments are present at the surface surrounding the dome, and a thin veneer of Holocene eolian deposits exists over the dome. Holocene sediments surrounding the dome are alluvial, bay, and marsh deposits that rarely exceed 30 feet in thickness. The eolian deposits over the dome are thin and rarely exceed 5 feet in thickness. The mode of deposition of these deposits is unique to the Gulf Coast; they are chiefly beds of clayey sand and silty sand. The source area for these sediments were beach cheniers to the south. Southerly winds from the Gulf have transported the sediments to this area where they were deposited on the topographically high surface of the area, the West Hackberry dome.

Holocene deposits are immediately underlain by the Pleistocene Prairie Formation. The Prairie Formation crops out over the dome and to the north of the site. Throughout southern Louisiana, the Prairie is comprised of alluvial, deltaic, bay and marsh, and littoral sediments. Clays of the Prairie Formation are oxidized and dessicated, which resulted when a drier, cooler climate existed during a low sea level stage in the late Pleistocene.

The Montgomery Formation of Pleistocene age disconformably underlies the Prairie in the subsurface over and adjacent to the dome. The base of the Montgomery is interpreted to be the base of the "A" sand (or "200-foot" sand, which is the upper sand unit of the Chicot aquifer in the area, Section 4.9.4). The depositional environment of the Montgomery was alluvial and deltaic.

The Bentley Formation, also of Pleistocene age, disconformably underlies the Montgomery in the West Hackberry vicinity. The base of the Bentley is interpreted to be the base of the "B' sand (or "500-foot" sand of the Chicot aquifer). The basal Bentley is a gravelly sand that fines upward and grades to deltaic deposits.

The Williana Formation, which is the oldest Pleistocene formation in Louisiana, disconformably underlies the Bentley over and adjacent to the dome. The basal Williana sand is interpreted to include the "C" sand (or "700-foot" sand of the Chicot aquifer). It has been reported that sediments interpreted to be of the Williana extend to cap rock over the dome47. The Williana is a gravelly sand at its base and fines upward to clay deposits.

The Williana Formation disconformably overlies the Pliocene sediments adjacent to, and perhaps over, the dome. No formal stratigraphic name is recognized in the subsurface for the Pliocene sediments. Pliocene units, if present, are thin over the dome proper and thicken in all directions off the dome. They are generally fossiliferous clay sediments.

Late and middle Miocene sediments have not been identified over the dome but are present in the subsurface around the dome. The absence of these sediments on the dome indicates a period of diapiric uplift and erosion post mid-Miocene time.

Below the Miocene sediments, fauna assigned to the Marginulina Zone are encountered in the subsurface surrounding the dome. These sediments are of Oligocene age and correlate with the Anahuac Formation of Louisiana.

4.4 STRUCTURAL GEOLOGY

4.4.1 Subregional Structural Setting

The West Hackberry salt dome is located on the northwest flank of the Calcasieu Lake salt withdrawal basin (collapse basin). In addition to the Hackberry salt mass, the basin is surrounded by the large salt masses, including Big Lake, Sweet Lake, and Creole structures, which flank the basin to the northeast, east, and southeast, respectively. The center of the basin is near the Calcasieu Lake dome (Section 6.6), and the Hackberry ridge is located approximately 11.5 miles northwest of the basin center.

East and West Hackberry domes are believed to be parts of a very large, single salt ridge (Section 6.4). If connected, these two domes together form a buried salt ridge at least 6-l/2 miles long and greater than 2 miles wide. East Hackberry dome lies about 1 mile northeast of West Hackberry dome. The top of East Hackberry dome lies at a greater depth than West Hackberry: the cap rock at East Hackberry was encountered at 3,000 feet and salt at about 3,500 feet versus 1,500 feet and 2,000 feet, respectively, at West Hackberry47.

4.4.2 Faulting in the Hackberry Area

Fault patterns and geometry at West Hackberry dome were evaluated from remote sensing imagery, borehole geophysical logs, and a series of geologic sections and structure contour maps constructed for this study (Figures 4.4 through 4.15). The structural analysis was initially based on remote sensing imagery analysis (Figure 4.5) and by a structural analysis of the "B" sand based on the log data (Figure 4.6).

Details of the remote sensing imagery analysis for this study are described in Appendix B. This remote sensing imagery analysis was conducted so as to include an area larger than the dome in order to develop an overall understanding of the through-going structure. Alignment of apparent geomorphic features and tonal anomalies on aerial photographs provide surface clues to subsurface structure. Linear trends of topographic and drainage features and of vegetation and moisture differences were plotted (Figures 4.2 and 4.3).

Plotted lineaments generally trend northeast-southwest and northwest-southeast in the study area. Some of the lineaments are better developed than others and were evident on several sets of the aerial photographs. Moisture differences, as defined by linear vegetation contrasts or aligned vegetation, indicate probable young fault activity. The major structural pattern observed over the dome is a horst and graben complex of faults trending northeast-southwest (Figures 4.5, 4.6, and 4.10 through 4.15). Radial faulting on the flanks of the dome trend primarily northwest-southeast (Figures 4.5 and 4.6). Such fault patterns are typical of salt domes, as described in Section 6.3.

Based principally upon the structure contour map of the lrBtr sand and upon fault histories of various Gulf Coast salt domes, the initial fault displacement probably was along the radial faults on the southeast and northwest flanks of the dome. Subsequently, the horst and graben feature defined by the major northeast-southwest trending faults developed across the rising salt ridge. As the dome continued to rise, the horst broke apart. Subsidiary radial faults extended across the central area, and the northeast and southwest flanks of the horst "subsided." As uplift progressed, additional subsidiary faults formed in wedge-shaped or triangular blocks.

Faulting exhibited by displacements of the "B** sand correlates closely with structural irregularities in the cap rock and on the top of the salt (i.e., re-entries, platforms, and steep gradients), which suggests that continued domal growth within the salt has induced a through-going fault system that has affected all of the sediments overlying the salt (compare Figures 4.5, 4.7 and 4.8). The salt has, presumably, also been affected.

4.5 SURFICIAL AND NEAR-SURFACE SOILS

This section presents a description of the surface and near-surface soils. This information is derived from available geotechnical r.ports[2,12,57,58,59,98,99]. Data presented in this section provide a general characterization of the soils over the dome and are not necessarily representative of a specific location.

4.5.1 Geotechnical Properties of Surficial Soils

The surface layer at the West Hackberry SPR Site generally consists of dark brown, collapsible silt, 1 to 2 feet thick. Collapsible silt is a soil that, when loaded and wetted, will decrease in volume rapidly. The silt layer generally is underlain by stiff clay. The surface soils are different on the pimple mounds, which are quite numerous across the site: cross sections of these mounds indicate 1 to 2 feet of light brown, sandy silt; and local dark brown, collapsible silt at the surface underlain by stiff clay. The light brown, sandy silt generally is not present between mounds. The results of laboratory testing indicate that this light brown, sandy silt is not collapsible.

4.5.2 Black Lake and Bayou Bottom Deposits

The soil profile in Black Lake generally consists of a surficial zone of very soft clayey silt underlain by firm to stiff, brown and gray, silty clay, as indicated by the results of a test boring and 10 probes conducted in the bottom sediments8. The surficial, very soft zone varies in thickness from about l/2 to 2-l/2 feet. From laboratory tests, this zone is classified predominantly as a low plasticity silt.

A similar investigation was conducted in the bayou that separates brine wells 1 and 25g. Water in this bayou is generally 1 to l-1/2 feet deep, except where an old dredged channel was encountered; there, the water is 3-l/2 feet deep. The bayou bottom deposits are similar to the bottom deposits of Black Lake: a very soft clayey silt ranging in thickness from 6 to 18 inches and overlying a medium to stiff clay.

4.5.3 Generalized Soil Profile and Summary of Foundation Recommendations

Based on information from sample descriptions of a go-foot-deep boring advanced at the location of the intake structure on Black Lake, 50-foot borings conducted for a seismic survey, and various shallower borings and test pits, a general subsurface soil characterization is as follows:

- Stratum 1 - Surface veneer of light gray to light brown silt or sandy silt: generally collapsible.

- Stratum 2 - Upper 40 to 45 feet of firm to very stiff dessicated clays; locally sandy and/or silty.

- Stratum 3 - Below about 45 feet, the stratigraphy generally remained a stiff to very stiff dessicated clay with occasional thin layers of silt and/or sand.

From available boring logs and various stratigraphic descriptions in previous reports, the soils at the site are interpreted as consisting of a surface veneer, predominantly of silts, overlying the Prairie Formation clays. The soil units at the West Hackberry SPR Site appear to be very similar to late Pleistocene soils throughout the Gulf Coast.

The consensus of recommendations from the geotechnical reports was to strip or remove the collapsible soil from all well pad locations. If necessary, grade should be reestablished by compacted structural fill, using on-site soils. The recommendations for subgrade treatment of roadway embankments was to leave the collapsible soils, where present, in place. Roadway embankments would be placed utilizing on-site, non-collapsible soils as fill. This fill would require moisture and compaction control. Some localized settlement and rutting was projected to occur in the roadway embankments during the construction period and maintenance would be required before the project was completed.

4.6 EXPLORATION HISTORY

The exploration history of the West Hackberry dome is lengthy, dating to 1901. A great deal of information on early exploration on and around the dome is not available because of a lack of records; nevertheless, a rather extensive history can be constructed.

Exploration for oil began on the dome in 1902, but it was not until some 26 years later that oil was discovered. It was also about this time that extensive exploration for sulfur began, but there are no records to indicate that the dome was mined for sulfur.

Olin Corporation and its predecessors have been producing brine since 1934. Five of the caverns derived from their brine operations formed the initial storage sites for the SPR program at West Hackberry. Cities Services has developed 11 caverns on 80 acres southeast of the site. These caverns are presently used for hydrocarbon product storage.

Although there has been extensive exploration and exploitation of the dome in the vicinity of the West Hackberry SPR Site, there is little detailed information on the internal constituents of the dome or cap rock. Further exploration efforts are currently underway in support of the SPR program. Information on hydrocarbon exploration is summarized in the following sections. Additional information on exploration related to mineral exploration and exploitation is included in Section 5.5, Cap Rock Exploration, and in Section 6.6, Salt Development. Emphasis in each case is placed on those features that are in proximity to the West Hackberry site and could impact its development.

4.6.1 Exploration Records

Exploration wells drilled on and around the West Hackberry dome are generally cased with 9-5/8-inch casing (or comparable). The current practice when plugging and abandoning wells is to place a 200-foot plug at 800 to 1,000 feet, and a lo-foot cement plug at or near the surface. This plugging procedure, with few modifications, has been in use for the past 40 years. Prior to that time, stringent controls were not in effect, and complete records were not kept on plugging procedures. It is important to note that there are abandoned wells that have no record of ever being plugged, and a great many wells in the area that are not on record also may never have been plugged. This is illustrated by the fact that some 54 wells were drilled between 1902 and 1928, yet only two wells are listed in the State's records prior to 1927125. An unplugged well or an improperly plugged well can act as a conduit for deep, lower quality, ground-water brine or petroleum products to move up section and contaminate shallower fresh-water aquifers and/or for surface contaminants to move downward.

Figure 4.4 shows the location of wells on file with the Department of Conservation in Lake Charles, Louisiana, and the U.S. Geological Survey, Baton Rouge, Louisiana, which fall inside or near the 3,000-foot contour. Appendix A is a listing of locations, completion dates, total depths, plugging depths and dates (where available), and other pertinent information for all wells that appear on Figure 4.4. There may be some wells on and near the site that do not appear on the map because of the lack of records of the early exploration of the West Hackberry dome.

4.6.2 Hydrocarbon Exploration

The West Hackberry dome was discovered in 1901 because of its positive topographic expression, gas seeps and paraffin dirt, and by seismic refraction surveys[125].

Drilling

Exploration drilling began in 1902 and, over the course of the next 26 years, 54 wells were drilled without a discovery. On December 1, 1928, the Cameron Oil Company, Bycade Oil Corporation's Duhon No. 1 was completed as the first discovery in the Miocene at a depth of 3,154 feet. The well had a cumulative production of 1,200 barrels (bbls) of oil. A total of 24 pay zones have subsequently been identified in the Miocene-Pliocene sands between 3,095 and 9,813 feet. As of 1962, the deepest test was in the Miocene at a depth of 13,071 feet. Total production as of 1977 was 123.4 million barrels of oil and 113.7 billion cubic feet of gas (Louisiana Department of Conservation, personal communication).

There were three periods of increased exploration, the first in the late 1930's, then in the early 1950's, and a current resurgence due to the relatively high price of domestic crude oil, casing head gas, and gas condensate. Several rigs are continuously in service in the field, either on new production or on workover. The principal leaseholders are Amoco Production Company, Sutton Oil Company, W. T. Burton, and Superior Oil Corporation.

Geophysical Exploration

Various geophysical methods have been employed at and near West Hackberry, largely for the exploration of oil and gas, and to a lesser degree in search of sulfur. Seismic reflection and refraction surveys have been undertaken to aid in exploration of oil and gas, while gravity surveys have been conducted to locate additional salt domes and to delineate the limits of the cap rock and salt.

Seismic Exploration

Reference was made to seismic refraction profiles which aided in the discovery of the West Hackberry dome[122]. However, efforts to find and ultimately obtain these and other seismic data have not proved successful. Geophysical brokerage firms that were contacted indicated they could find no records of seismic refraction surveys at West Hackberry. However, they had records of reflection profiles that had been run by Amoco Production Company, the locations of which are shown on Figure 4.16). These lines were shot at various times: Line 1 in 1963; Lines 2, 4, 6, 7, 8, and 9 in 1965; Line 3 in 1967; and Line 5 in 1973. Amoco Production Company was contacted to allow inspection of the lines. All lines, except Line 5, had records that began at a depth of approximately 4,000 feet and were not of sufficient resolution to define the edge (flanks) of the salt. However, Line 5 had a record which began at approximately 1,000 feet and had sufficient resolution to define the top of the cap rock, the top of the salt, and the north flank of the salt. Amoco Production Company subsequently declined to sell the line, reportedly because the shooting techniques employed were still considered proprietary.

Gravity Survey

During the 1950's and 1960's, several gravity surveys were conducted in this portion of Louisiana for both petroleum and sulfur exploration programs. The initial surveys were of a regional nature, with a station density of two or three stations per square mile. The regional data are available through various geophysical data brokerage firms; however, they were not purchased for the West Hackberry SPR Site characterization study because of the limited site specific information they could provide.

During 1960, a more detailed survey was conducted. Approximately 2,500 stations were occupied in a 220-square-mile area centered on West Hackberry dome. It was a combination land, marsh, and water survey. The marsh work was conducted with a helicopter and a land meter. The water work was conducted with a boat, using a remote-controlled meter. All the data were tied together with a land survey. Over all, it was a tightly controlled survey., The station density of 10 to 12 stations per square mile allowed the data to be contoured at a 0.2 mgal interval.

Arrangements to purchase these data were not completed until June 1980. The data are included in a supplementary report on the Site Specific Geophysical Surveys at West Hackberry.

4.7 SUBSIDENCE

Based on an analysis of a series of aerial photographs, it is recognized that, during the past 25 years, the surface area of Black Lake has increased from about 4 square miles to between 25 to 50 square miles (depending upon the lake boundaries designated) (Figures 4.1, 4.2, 4.3). This change in lake size is presumably due to subsidence in the Black Lake area. The precise amount of subsidence is unknown as there are no leveling data in the immediate area of Black Lake. Vertical control was run north-south along State Highway 27 through Hackberry in 1965 by the National Geodetic Survey (formerly, Coast and Geodetic Survey)l12. That survey has not been repeated and the isolated data are of minimal value in projecting subsidence. However, based upon the changes in lake size and the projected changes in elevation required to produce inundation, it is estimated that approximately 3 to 5 feet of subsidence of the Black Lake area has occurred between 1933 and 1978.

Active regional subsidence of the Gulf Coast Geosyncline continues because of the downwarping of the basement due to regional tectonics and compaction of the thick sedimentary prism that has been deposited within the Gulf Basin. However, the rate of subsidence attributable to the geosyncline is very low and does not account for the substantial change in Black Lake.

Another process that leads to subsidence is withdrawal of subsurface fluids (i.e., ground-water pumpage and hydrocarbon extraction) and consequent decrease in fluid pressure. This decrease in fluid pressure results in an increase of the grain-to-grain pressure and, subsequently, compaction of the confining materials often observed at the surface as subsidencel". A comparison of water level contour maps from 1952 and 1970 shows a change in head of 41 feet at West Hackberry20r126. It is possible that some subsidence has occurred as a result of this decrease in head in the aquifers around the dome. However, the projected subsidence from such a small decrease in head does not account for the total subsidence observed at Black Lake.

Ground-water development near West Hackberry is probably not as significant as petroleum production. Latest production figures through 1977 for the West Hackberry oil field are 123 million barrels of oil and 113 billion cubic feet of gas (Department of Conservation, personal communication). This large-scale withdrawal of hydrocarbons, together with the concomitant production of brine, may have resulted in compaction of confining materials and surface subsidence, with a resultant increase in the size of Black Lake.

The shoreline of Calcasieu Lake and the Gulf shoreline south of Calcasieu Lake, as observed in aerial photographs and LANDSAT imagery, do not show dramatic changes over time as would be expected if regional subsidence or sea level change had been dramatic since 1930. Thus, the increase in the area of Black Lake appears to be due to local causes rather than regional phenomena. Oil and gas production, combined with the ground water removal for hydrocarbon development at the West Hackberry field, appear responsible for the largest fluid withdrawals and consequent subsidence of the Black Lake area.

4.8 SURFACE-WATER HYDROLOGY

4.8.1 Drainage Basin and Flood Plain Description

The West Hackberry SPR Site is located in the southern part of the Calcasieu River basin. The Calcasieu River basin encompasses a drainage area of approximately 4,450 square miles. Tributaries located in the upper 3,170 square miles of the basin range from flat, sluggish streams to moderately flowing streams. The southern portion of the drainage basin (including the vicinity of the West Hackberry SPR Site) is flat marshland dotted with several lakes. The largest of these is Calcasieu Lake, which covers an area of approximately 75 square miles. The Calcasieu River flows into Calcasieu Lake and Pass and ultimately empties into the Gulf of Mexico about 5 miles south of the lake (Figure 4.6). Black Lake is connected with the Calcasieu Lake system through Black Lake Bayou (Figure 4.5).

A major portion of the lower Calcasieu River basin has an average ground elevation of about 1.5 feet above mean sea level and is influenced by tidal fluctuations. The coastline of the Calcasieu Parish area differs from other parts of the Texas-Louisiana coastal areas in that there are no barrier islands or bay systems; rather, this coastline is characterized by a narrow, wave-cut beach and a landward series of beach ridges beyond which lie coastal marshes.

4.8.2 Topography and Site Drainage

The West Hackberry SPR Site and surrounding area can be categorized topographically as flat to low wetlands with the exception of the elevated area overlying the salt dome south and southeast of Black Lake. Elevations at the site range from about 5 feet above mean sea level near Black Lake to over 20 feet in the central SPR facility area. Natural site drainage has been altered by construction: however, generally drainage is radial, away from the central area.

4.8.3 Climatology

The West Hackberry SPR Site lies in the westernmost portion of the humid climatological zone of Louisiana and usually has mild winters. Mean annual precipitation for the area is approximately 54 inches per year, and the mean annual temperature is 700+4,115. Table 4-2 summarizes the total precipitation recurrence interval for a 24-hour rainfall duration at West Hackberry, based on published information117.

The average annual runoff for the upper portion of the Calcasieu River basin is approximately 22 inches115. Streamflow estimates for the lower Calcasieu River basin are not available because of tidal effects.

4.8.4 Flood Characteristics

Floodwater levels in the West Hackberry SPR Site area are influenced by tidal fluctuations, hurricane and other storm surges, and torrential rains and runoff. These factors interact to differing degrees in various parts of the Calcasieu River basin.

The Calcasieu River system is strongly influenced by tides, particularly in its lower portions, due to limited ground relief and proximity to the Gulf of Mexico. This is attested to by the absence of any stage-discharge relationships for the river downstream of Kinder, Louisiana (approximately 45 miles northwest of the site), and by the presence of marshes throughout the lower Calcasieu River basin.

The Calcasieu River basin has experienced many hurricanes and tropical storms that have caused loss of life and damage to property. The average frequency of occurrence of tropical storms and hurricanes for this area is about 1.7 storms per 100 years per 10 nautical miles of coastlinea5. The low coastal marshland assumes hydrologic characteristics similar to a shallow bay during hurricanes and is usually inundated well in advance of the arrival of the main thrust of the hurricane. The hurricane winds set up the ocean surface and drive the water inland. The broad expanse of marshland has significant influence on retarding the propagation of hurricane surges farther inland.

Recent hurricanes that have affected this area include Audrey in 1957, Carla in 1961, Hilda in 1964, Edith in 1971, and Carmen in 1974. The hurricane that had the most impact in the vicinity of West Hackberry was Hurricane Audrey in 1957. Its storm center passed approximately 5 miles to the west of the site (Figure 4.17). Near the coastline of Cameron Parish, Audrey generated a surge of 12 feet that diminished as it moved inland. The town of Hackberry recorded a peak surge of 6.7 feet[10].

The project area is also subject to periods of intense rainfall that may occur throughout the year. This rainfall is associated with tropical storms that normally occur from June through October. A review of published data indicates that flooding in the upper Calcasieu River basin is primarily due to riverine overflow: whereas, in the lower parts (including the West Hackberry SPR Site) flooding is totally hurricane-induced[88].

Peak discharges for the Calcasieu River at Kinder, Louisiana, have been monitored by the USGS since 1939[88]. For the period of record, the largest flows at Kinder occurred in August 1940 and May 1953. A stage recording gage located near Hackberry, Louisiana, has recorded peak stages for Calcasieu River and Pass since 1944. For the period of record, maximum stages at this Hackberry station occurred in June 1957 (Hurricane Audrey) and September 1961 (Hurricane Carla). The differences in extreme years, between the Kinder and Hackberry gages, imply that the flooding events at the two stations are independently generated. While flooding at Kinder and points upstream is due to stream overflow, flooding at Hackberry and points downstream is related to hurricane effects.

The degree to which overflow of the Calcasieu River contributes to hurricane-induced floods was not calculated by previous investigators. Furthermore, based on the information available, it does not appear feasible to differentiate between contributions from torrential rain and runoff and contributions from the flooding caused by wind-induced storm surge for the extreme stages at Hackberry. Qualitative analysis suggests that flooding at Hackberry, caused by the 1957 and 1961 events, was due primarily to hurricane-induced storm surges. However, local flooding from torrential rain certainly affects this area, as evidenced during May 1980.

4.8.5 Coastal Storm Surge Flood Studies

The West Hackberry SPR Site is situated within the hurricane coastal flood zone (Figure 4.18). Two studies by Federal agencies and consultants have directly addressed the hurricane-induced flooding of the Cameron Parish area[110,113]. A third study has been conducted for the Sabine Pass area, immediately west of Cameron Parish[111]. The Federal Emergency Management Administration is currently funding a new study for Cameron Parish.

The earlier Army Corps of Engineers study was made for the Federal Insurance Administration to provide flood elevations for the Louisiana coast"'. In this study, a design storm approach was used. Hurricane parameters compiled from historical storm records of the period 1900 to 1970 were analyzed to construct a synthetic hurricane of which the properties (i.e., central pressure, maximum winds, and size) have a recurrence interval of 100 years. This synthetic hurricane was then used to compute the loo-year surge level. The general coastline was represented by a smooth line called the surge reference level (SRL). Storm surge was computed using a simplified one-dimensional model along a traverse, perpendicular to the SRL. The peak surge computed on the coast was then allowed to gradually decrease inland according to a linear relation calibrated by historically recorded high water marks.

From this model, the loo-year flood elevation was computed to be 12.8 feet above mean sea level on the coastline near the Cameron Parish area. The loo-year flood elevation, estimated by this study for the West Hackberry SPR Site and vicinity, is 6.5 feet above mean sea level.

The results of a second flood insurance study for the same area were used to revise the 1970 Federal Insurance Administration flood insurance map for the Cameron Parish area[113]. The study used techniques similar to the Army Corps of Engineers study, involving a design storm approach and a one-dimensional, open-coast surge model. However, some modifications, based on the data collected for Hurricane Audrey, were incorporated for characterizing the loo-year hurricane. In addition, while the Army Corps of Engineers technique reported the maximum surge height at the point where the design storm crosses the shore, the second study averaged the surge heights calculated for several coastal points across the width of the affected zone. Therefore, the value for the loo-year surge height (averaged over the length of coastline) can be expected to be significantly lower than the Army Corps of Engineers loo-year surge height, which is the maximum for the design storm.

The loo-year surge level for the second study was estimated to be 9.5 feet above mean sea level near the Cameron Parish coastline (Figure 4.18)l13. From the method for determining overland flooding, the loo-year flood elevation at the West Hackberry SPR Site and vicinity is approximately 4.5 feet above mean sea level (Figure 4.18), which is 2 feet lower than the flood level computed by the Army Corps of Engineers study"'.

The Army Corps of Engineers flood insurance study for the Sabine Lake area used a method of study similar to the previously discussed studies for computing the open coast surge levelslll. However, a more sophisticated two-dimensional model was used to compute the surge levels as the surge moves into the inland bays and estuaries. From this study, a loo-year surge level of 14.0 feet above mean sea level was estimated for near the coastline south of Sabine Lake, Texas, and about a 10.5-foot surge level at an area equidistant inland as is West Hackberry[114]. Although this study is not directly applicable to the Cameron Parish area, the general resemblance of the overall topography and physical environment of the Texas-Louisiana coastal area suggests that similar loo-year surge levels could be expected at both the Sabine and Cameron parish areas. However, it cannot be readily evaluated whether or not the higher loo-year surge level estimated by this study resulted from the more sophisticated method, or from actual differences between the Sabine Lake and Cameron parish areas.

Cameron Parish is currently being restudied under contract to the Federal Emergency Management Agency. This new study is utilizing the most recent methodology, known as the joint probability approach, to describe the storm statistics characteristic of the study area, as opposed to the conventional storm design method used in the previous studies. Furthermore, a two-dimensional, open-coast and bay model will be used to compute the storm surges near the coast, which then will be propagated overland by another numerical technique. With the use of these study methods, it is anticipated that this study will present better and more accurate lo-, 50-, loo-, and 500-year recurrence interval surge levels for the West Hackberry SPR Site. The study is projected for completion by mid-1981.

4.9 GROUND-WATER HYDROLOGY

4.9.1 Regional Ground-Water Conditions

Ground water developed in southwestern Louisiana is essentially obtained from three major aquifers: the Jasper of Miocene age, the Evangeline of Miocene-Pliocene age, and the Chicot of Pleistocene age. "Chicot-Atchafalaya aquifer" is a commonly used description in the eastern portion of south-western Louisiana where the Chicot and Atchafalaya aquifers are hydraulically continuous38. However, the Atchafalaya aquifer is limited to the Mississippi alluvial valley and is not present in the area of study. These aquifers, and associated sediments, are part of a thick accumulation of alternating sands and shales (mudstones) that were deposited in a deltaic environment similar to the modern Mississippi River delta.

The Jasper, Evangeline, and Chicot aquifers are present in the study area, and the Chicot and Evangeline aquifers are probably present at the site. The Jasper aquifer is thought to be truncated locally by the salt dome. The actual geometry of these aquifers near the site is difficult to assess because of their lithologic similarity. Figure 4.19, which presents a hydrogeologic cross section through the study area that passes just east of the site and off the West Hackberry dome, illustrates the regional geologic characteristics of the aquifers. Of particular note is the approximate location of the freshwater-saltwater contact. Fresh water is generally defined as containing 250 mg/l, or less, of chloride for ground-water studies in southwest Louisiana. Salt water has greater than 250 mg/l chloride. Potable water is that containing less than 1,000 mg/l total dissolved solids (TDS).

The Jasper and Evangeline aquifers are saline aquifers in the study area. The sediments that make up these aquifers were deposited along the ancient Gulf Coast in much the same manner that the Mississippi River is depositing sediments near New Orleans. Consequently, the waters in these sediments, during time of deposition, had a salinity close to that of sea water (10,000 to 30,000 mg/l). After deposition of the sediments and withdrawal of the sea, fresh water gradually has flushed the aquifers, driving the salt water toward the Gulf. Thus, the salt water in aquifers in the study area is probably due more to incomplete flushing than to salt-water encroachment from the Gulf.

Because of the absence of fresh water in the Jasper and Evangeline aquifers, only a limited discussion of each is presented here; the Chicot aquifer is given the major emphasis.

4.9.2 Jasper Aquifer

The Jasper aquifer is contained in sediments of Miocene age. As discussed in Regional Stratigraphy (Section 3.3), the Miocene sediments consist primarily of deltaic deposits. Formal formational names are generally not used for Miocene sediments in the subsurface. The beds of the Jasper aquifer dip toward and increase in thickness toward the southeast. Near Lake Charles, the beds dip southerly, approximately 83 feet per mile, and are approximately 3,420 feet thick.

Recharge to the Jasper aquifer occurs principally in central Louisiana where the aquifer is overlain by Pleistocene terrace and Holocene alluvial deposits. The regional ground-water trend is downdip to the southeast and is only locally affected by pumpage. Discharge is through upper, confining layers into the Evangeline aquifer, as well as by pumping. Most natural discharge takes place in southern Beauregard, Allen, and Evangeline parishes, where the discharge occurs through interconnecting sands or along the Bancroft-Mamou and Tepetate-Baton Rouge fault systems. Discharge also occurs along the Sabine and Calcasieu rivers through the overlying Evangeline and Chicot aquifers. Hydraulic characteristics of the Jasper aquifer are listed on Table 4-3.

Based on our evaluation of the geologic data available, the West Hackberry dome has apparently truncated the Jasper aquifer; thus, the aquifer is projected as being absent in the site vicinity.

4.9.3 Evangeline Aquifer

The beds of the Evangeline aquifer dip toward the southeast, and the dip and the thickness increase toward the south. North of the study area, in Vernon Parish, the dip is approximately 20 feet/mile, increasing to 40 feet/mile in northern Calcasieu Parish. The thickness ranges from approximately 500 feet north of the study area to 3,000 feet in the vicinity of Lake Charles.

The Evangeline aquifer is recharged in central Louisiana, where the aquifer is overlain by Pleistocene terrace deposits. The aquifer is also recharged in the northern part of Beauregard, Allen, and Evangeline parishes, where ground-water pressure is slightly higher in the Chicot aquifer than in the Evangeline aquifer.

The regional ground-water gradient is generally down, toward the southeast. However, the waters move up section in a generally stair-step fashion, through interconnecting sands, toward areas of natural discharge. Movement into the overlying Chicot aquifer is accelerated in areas where heavy pumping from the Chicot creates large head differences across confining layers.

As in the case of the Jasper aquifer, it is assumed that faulting plays an important role in the upward movement of ground water. The water moves up fault planes where sands of higher hydraulic head are opposite sands of lower head.

Natural discharge takes place into the Sabine and Calcasieu rivers in areas where sand and gravel of the Chicot aquifers have been stripped by erosion, exposing sands in the lower part of the Evangeline aquifer.

Hydraulic characteristics of the Evangeline aquifer are listed on Table 4.3.

4.9.4 Chicot Aquifer

The name "Chicot aquifer" is assigned to a group of fluvial Pleistocene-age sands of the Williana, Bentley, Montgomery, and Prairie formations that overlie the Evangeline aquifer. These formations dip slightly, and increase in thickness toward the south.

The Chicot aquifer is the principal source of ground water in the study area. In 1975, 74 billion gallons of water were pumped from the Chicot aquifer in Cameron and Calcasieu parishes (Table 4.4)88. Most of the ground water pumpage in Calcasieu Parish, approximately 119 million gallons/day, is for industrial purposes, followed by 56.6 million gallons/day for rice irrigation. The effects of this pumping on regional and local subsidence is discussed in Section 7.

In the study area, the principal water-bearing sands of the Chicot aquifer are the "200-foot," *'500-foot," and "700-foot" sands, named for their depth in the Lake Charles area. At the West Hackberry SPR Site, water-bearing sands, designated the "A," "B," and "C," sands, are found at depths of about 200 feet, 500 feet, and 700 feet. However, the correlation of these sands with the aquifiers at Lake Charles is uncertain, and the depths may be coincidental. Figure 4.4 shows the locations of water wells near the West Hackberry SPR Site, as listed by the Louisiana Geological Survey. Reportedly, some additional wells that tap the shallow aquifer are used locally for domestic and livestock supplies, but these wells are not listed with state or federal agencies.

The "200-foot" sand supplies water to irrigation, domestic, and public supply wells, as well as industrial wells in Lake Charles. The "500-foot" sand, which is the most utilized aquifer in the study area, supplies the bulk of water used for irrigation and industrial needs. The "700-foot sand supplies water to Lake Charles and some other public supplies. Hydraulic characteristics of each of these sands are listed in Table 4.3.

In the study area, the "A" sand is approximately 50 feet thick, and it grades from a coarse sand and gravel at the base to a fine to medium-grained sand at the top (a fining upward sequence). It is separated from the underlying 'B" sand by approximately 250 feet of predominantly clayey material.

Near the study area, the "B' sand is approximately 150 to 200 feet thick and exhibits the same fining upward sequence as the "A" sand. It is separated from the "Cl sand by approximately 50 to 60 feet of predominantly clayey material. Due to local thinning of this clayey material and the presence of interconnecting sands, considerable hydraulic communication exists between the 'B' and the "Cl sands.

As in the case of the "A" and 'B" sand layers, the "Cl sand exhibits a fining upward sequence. In several places, the 'C' sands within this unit are separated by clay layers. However, these clays are discontinuous, and the sands are hydraulically connected. The total thickness of the "C" sand is approximately 200 feet. Through most of its area1 extent, the underlying Evangeline aquifer is separated from the 'C" sand by approximately 100 feet of clayey material. However, locally occurring sands allow hydraulic connection between the two aquifers.

Overlying the "A" sand, at depths less than 100 feet, are aquifers of Pleistocene age composed of oyster shells and associated silty sands. These aquifers usually yield small quantities (less than 100 gallons per minute [gpml) of water for domestic and rural supplies. These shallow aquifer sands are normally thin and intermittent but, because of their proximity to the surface, these aquifers are relatively significant to the West Hackberry SPR Site. The material overlying these aquifers is often silty to sandy and, therefore, will transmit fluids, although slowly. In the event a spill occurs at the West Hackberry SPR Site, the shallow aquifer would be the one most affected. There is very little information available concerning the shallow aquifers, except that they provide much of the local domestic supply.

Hydraulic communication between the shallow sand aquifers and the "A" sand aquifer is probably low, due to intervening confining layers and low head differences across the confining layers, although some communication probably occurs along fault planes. It is likely that a high degree of communication exists locally between the shallow-sand aquifer and lakes, streams, and marshlands.

Water quality data on the various sands of the Chicot aquifer have been compiled by Harder36. Figure 4.20 shows the location of the freshwater-saltwater interface in southwest Louisiana for the '200-foot" sand. Chemical analysis of water from the "200-foot" sand indicates that it is a sodium-bicarbonate type and contains sufficient amounts of calcium and magnesium to make it moderately hard to hard36. Iron content is usually less than 1 mg/l, but locally, may reach 8.5 mg/l. Chloride is generally less than 100 mg/l, except in eastern Calcasieu Parish where it is as much as 300 mg/l, and total dissolved solids are as high as 700 mg/l.

Analysis of waters from the "500-foot" sand shows the water as moderately hard, of a pH range of 6.7 to 8.6, and with total dissolved solids of 302 mg/l. Figure 4.21 shows the location of the freshwater-saltwater interface as of 196638. Near West Hackberry dome, in Calcasieu Parish, chloride contents as high as 300 to 500 mg/l have been recorded. Some chloride concentrations, as high as 600 mg/l, are found from wells that are completed above salt structures. In Calcasieu Parish, total iron contents range from 0.04 to 11.00 mg/l, and in an average of 28 samples is 2.3 mg/136.

Figure 4.22 shows the location of the freshwater-saltwater interface in the "700-foot" sand. Chemical analyses of waters from wells screened in the "700-foot" sand indicate the water to be moderately hard and chloride concentrations generally higher than in either the "500-foot" or "200-foot" sands.

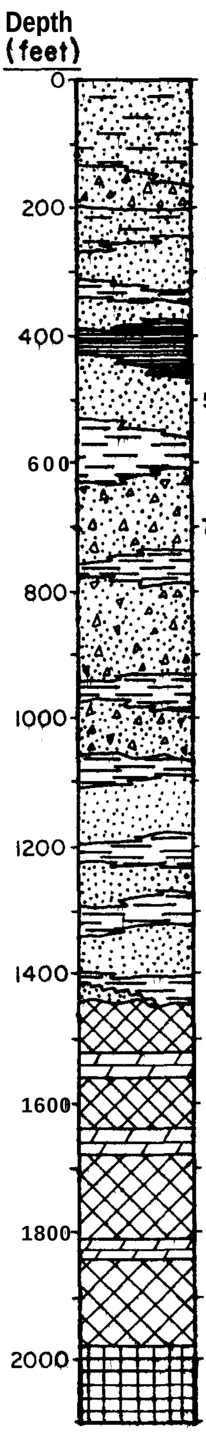
Recharge to the Chicot aquifier occurs in many areas: through the Atchafalaya aquifer in the Mississippi alluvial valley; and in northern Beauregard, Allen, and Evangeline parishes, where the Chicot crops out. Locally, at pumping centers where head differences are sufficiently high, considerable recharge probably takes place through vertical leakage from underlying aquifers.

The vast majority of discharge from the Chicot aquifer is by pumping. Pumping is so intense in the vicinity of Lake Charles that the regional ground-water gradient has locally been reversed from south to north (Figure 4.23).

4.9.5 Contained Methane

Water wells in the vicinity of the West Hackberry SPR Site generally yield rather high concentrations of methane along with the water. For example, one well, located approximately 2 miles south of the site, on the south flank of the dome, had a measured methane concentration of 100 parts per million (ppm)37. Figure 4.24 shows the distribution and occurrence of methane in southwestern Louisiana. The highest concentrations occur in areas of hydrocarbon production. The concentration of methane in water in these wells varies with: 1) their distance from the source of methane, 2) the length of time the well has been pumped, and 3) the pattern of pumping of nearby wells. In most of southwestern Louisiana, the methane is probably generated from organic debris within the aquifers. However, in the vicinity of some oil and gas fields, some methane probably originated in the oil and gas sands underlying the fresh-water aquifers37. The gas probably works its way upward along fault planes from the gas sands to the overlying fresh-water sand. Potential hazards at the site posed by methane are described in Section 7.

TABLE 4.1
LITHO-STRATIGRAPHIC COLUMN (GENERALIZED)
WEST HACKBERRY SPR SITE



Aquifer	Type of Material	Age	Group/Formation
	Clay and silt. Rich in organic matter.	HOLOCENE	Le Moyen
	Sand and gravel.		
CHICOT	Silt and clay, some shells	PLEISTOCENE	Prairie
200 foot sand	Blue- gray sand, grades downward into shale		?
			Montgomery
500 foot sand	Coarse sand		?
700 foot sand	Sand and gravel with intercalated clay layer		Bentley
			?
			Williana
	UNCONFORMITY		
EVANGELENE	Fine-to medium-grained sands interbedded with clay and lignite	PLIOCENE	Foley
	? ? ?		?
	sand. and clay	MIOCENE	Fleming
	UNCONFORMITY		
	Anhydrite and subordinate amounts af dolomite in irregular bands	? ? ?	Cap Rock
	Halite with anhydrite stringers near the top	TRIASSIC to JURASSIC	Louann Salt

TABLE 4.2

PRECIPITATION DATA
FOR
WEST HACKBERRY VICINITY

Recurrance Interval	Maximum Amount of Rainfall for 24-Hour Period
10 year	8.5 inches
25 year	10.5 inches
50 year	11.7 inches
100 year	13.3 inches

Source: U.S. Weather Bureau, 1963, Technical Publication No. 40

TABLE 4.3

HYDRAULIC CHARACTERISTICS OF AQUIFERS

Aquifer	Hydraulic Conductivity (K)* (feet/day) Range	Avg.	Transmissivi~v IT)* (feet2/day) Range	Avg.	Specific Capacity (SC)' (gpm/f00t) Range	Avg.	Storage Coefficient (s)*
Jasper	40-100	N/A	1,200-20,000	N/A	2-77	N/A	N/A
Evangeline	30-100	N/A	l,OOO- 2,000	N/A	5-26	N/A	0.0002
Chicot							
"200-foot" sand	107-201	N/A	N/A	34,759	N/A		0.00086
"SOO-foot" sand	133-267	160	N/A	26,737	6-75	40	0.00054
"700-f00t" sand	N/A	160	N/A	24,064	N/A	30	0.0006

*Definitions of hydraulic terms follow.
N/A: Not available
Source: Harder, 1960

TABLE 4.3 (continued)

Definitions of terms used in Table 4-3 are as follows:

K = Hydraulic Conductivity

Hydraulic conductivity is defined as the quantity of water flowing during one unit of time through a face of unit area under a driving force of one unit of hydraulic head change per unit length. Stated in more general terms, hydraulic conductivity rates the ease, or difficulty, with which water moves through a porous medium. Hydraulic conductivity has units of velocity. A clean river sand typically has a K of 58 feet/day. This should not be confused with the velocity of ground-water movement. While K has the units of velocity, it is not the velocity of ground-water flow. It is simply the constant of proportionality in Darcy's flow equation. For the mathematical proof of Darcy's equation and hydraulic conductivity, the interested reader is referred to Domenico[15].

T = Transmissivity

Transmissivity is defined as the rate of flow of water, at the prevailing temperature, through a vertical strip of aquifer that is one unit wide and extends the full saturated thickness of the aquifer, under a unit hydraulic gradient. More simply stated, T is the product of hydraulic conductivity (K) and the saturated thickness of the aquifer. (K x saturated thickness = feet2/day.)

SC = Specific Capacity

Specific capacity is defined as yield per unit of drawdown of the water level in a pumping well and has units of volume per time (discharge) per unit decline in water level (i.e., gallons per minute per feet of drawdown). This term rates the strength of a well. The greater the specific capacity, the stronger the well. A good well typically has a SC of approximately 40 gallons/minute/foot of drawdown.

S = Storage Coefficient

The storage coefficient is defined as the volume of water released from, or taken into, storage per unit surface area of aquifer per unit change in head. More simply stated, the storage coefficient is the amount of water that is released from storage due to the expansion of water and the compression of the aquifer matrix. By definition, S is dimensionless.

TABLE 4.4

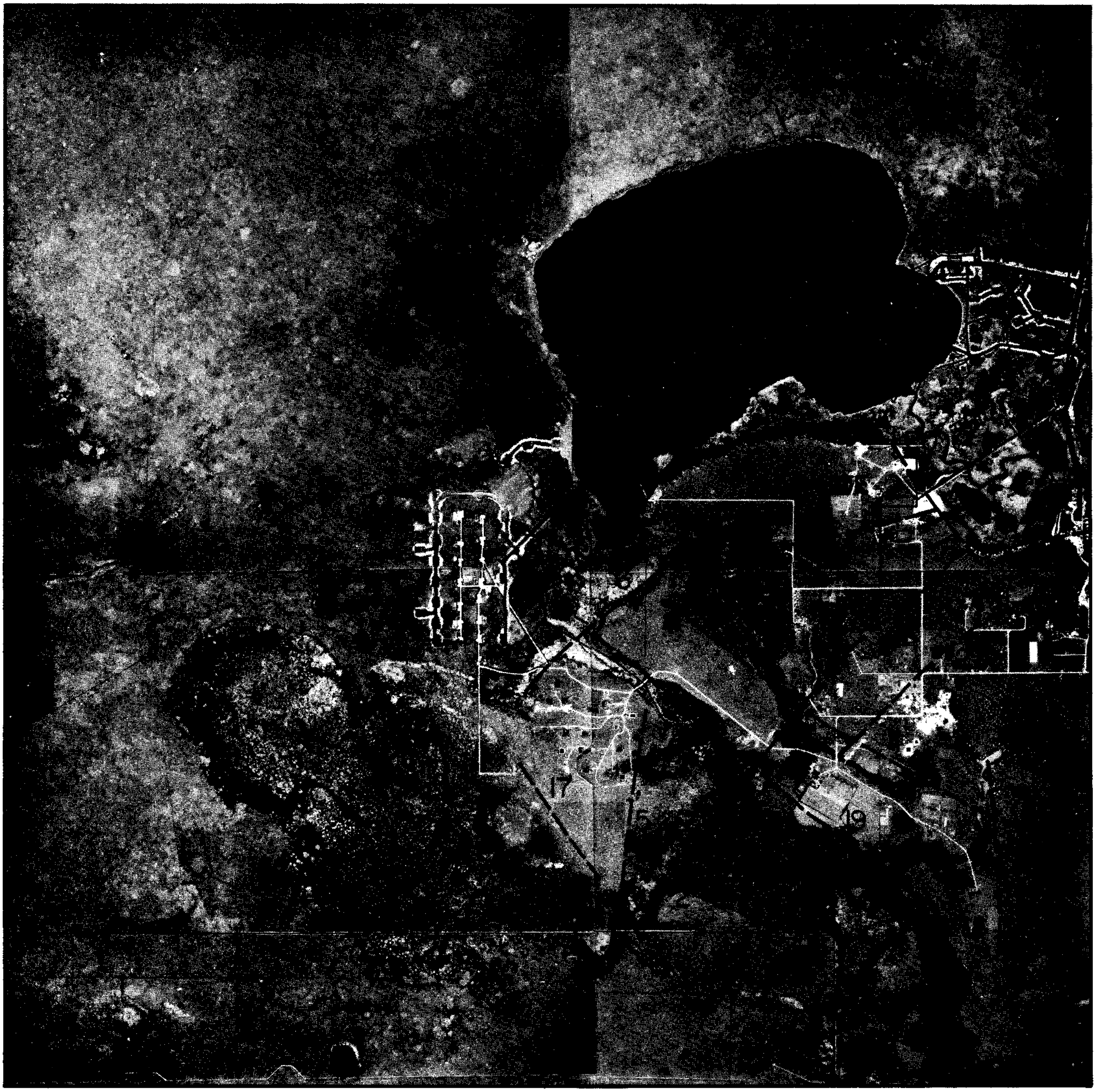
PUMPAGE OF WATER IN LOUISIANA BY PARISH, SOURCE, AND PRINCIPAL USE, 1975
(IN MILLIONS OF GALLONS PER BAY)

Parish	Public Supply		Industrial		Rural Domestic	Rural Livestock		Irrigation Rice		Irrigation Other		Total Use		
	a4	SW	W	SW	QA	Qd	SW	Qrl	SW	cw	SW	cu	SW	Total
Calcasieu	16.2		119.	314.	1. 37	0. 35	0.15	56.6	188.	1.40	1.40	194.92	503.55	698.47
Cameron	2.69		2.40		0.20	0.44	0.05	2.47	57.5			8.20	57.55	65.15

gw = ground wat.er
sv = surface water
Source: Cardwell and Xalker, 1979

Woodward-Clyde Consultants

Figure 4.1
1933 AERIAL PHOTO MOSAIC
OF WEST HACKBERRY SITE



EXPLANATION

4 Air photo lineaments

0 2000 4000 6000 feel

Note: For lineament identification and characteristics, see Appendix B

Figure 4.2
1955 AERIAL PHOTO MOSAIC
OF WEST HACKBERRY SITE

EXPLANATION

4 Air photo lineaments

Note: For lineament identification and characteristics, see Appendix B

Figure 4.3
1978 AERIAL PHOTO MOSAIC
OF WEST HACKBERRY SITE

Sandia coord for 111 492,642.52 N 1,343,359.73 E } scale: correctly

Cavern 111 1661.47 from west prop line 4030.25 from South prop line | with South prop line indicated

Woodward-Clyde Consultants

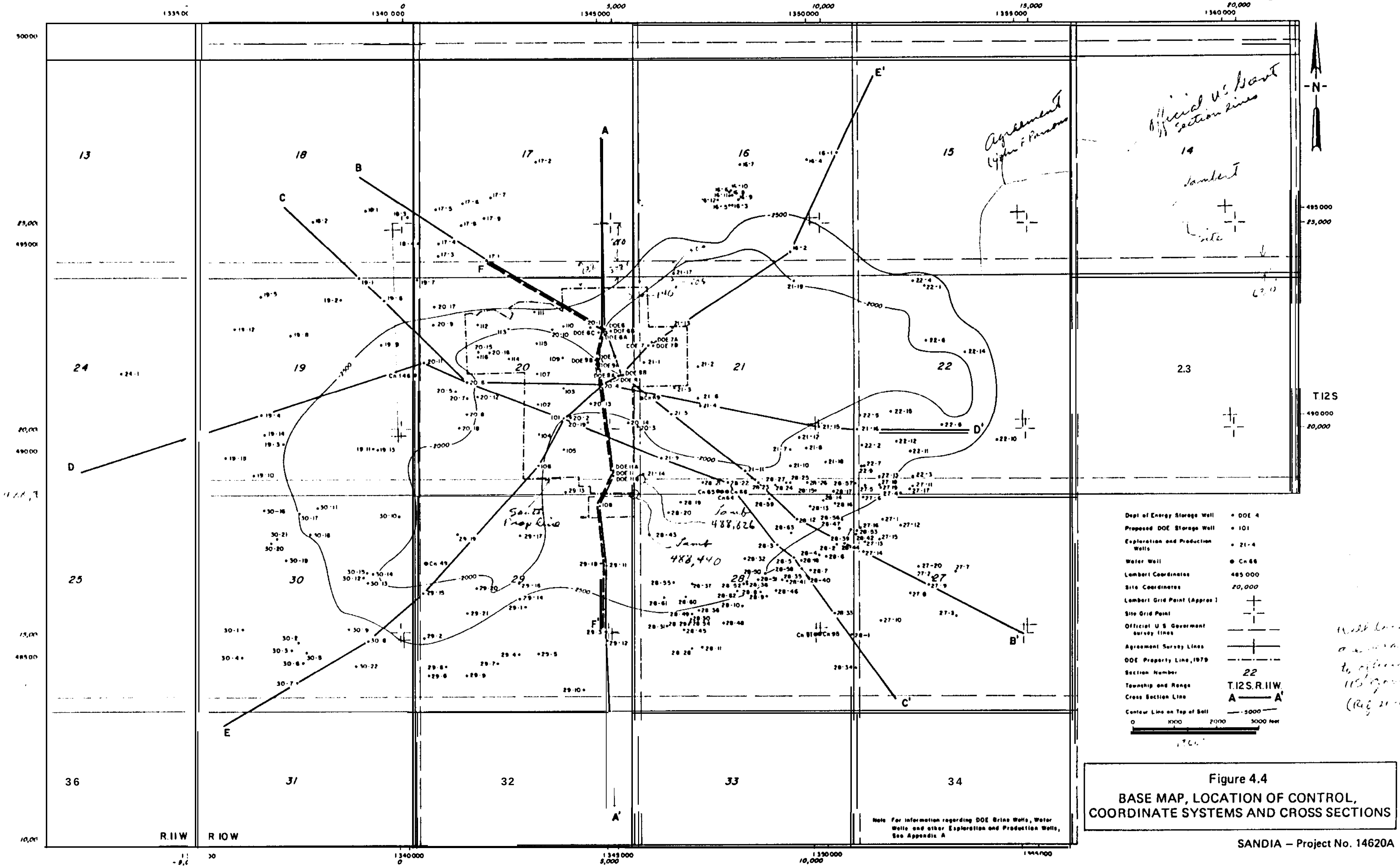


Figure 4.4
BASE MAP, LOCATION OF CONTROL, COORDINATE SYSTEMS AND CROSS SECTIONS

SANDIA – Project No. 14620A

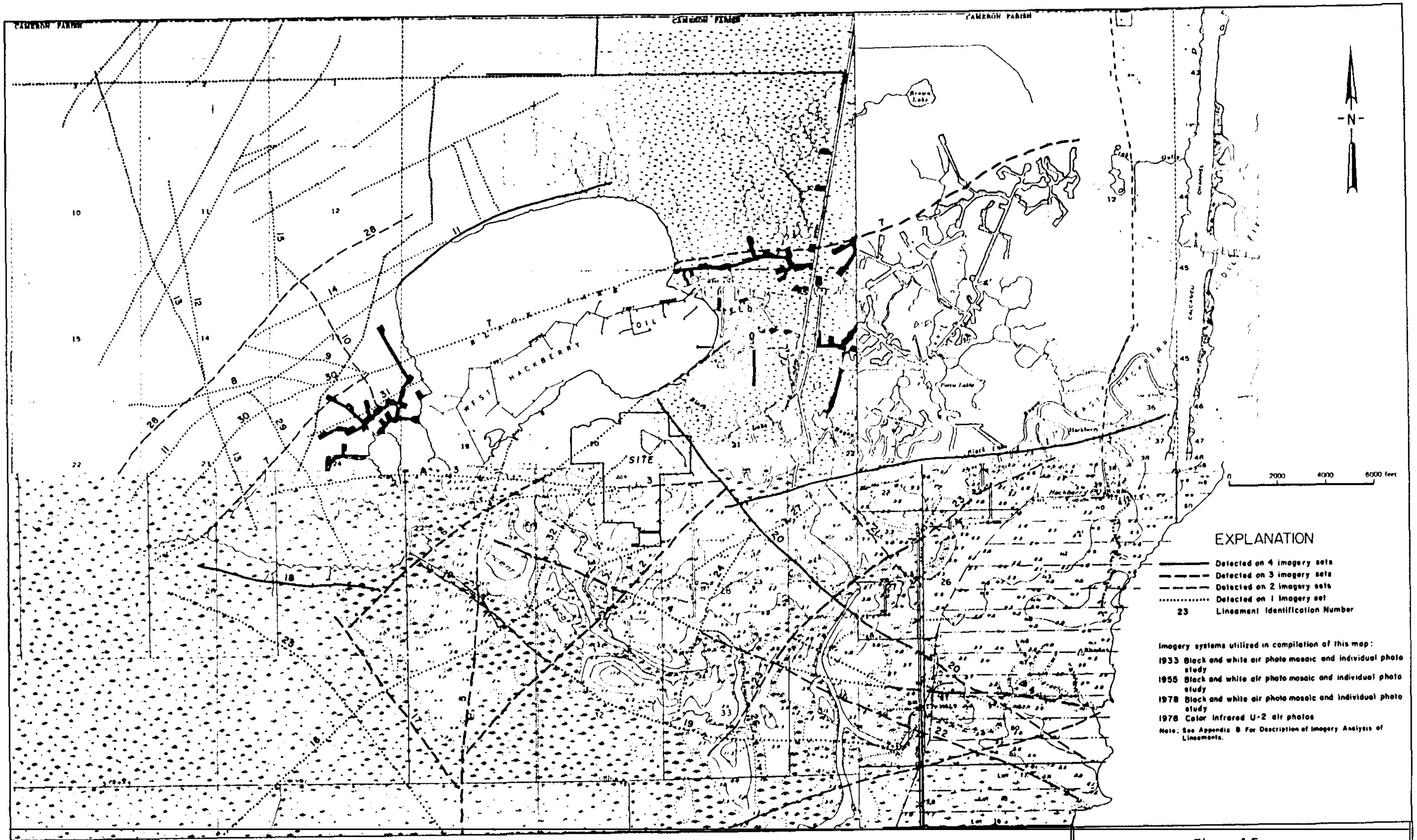


Figure 4.5
MAP OF LINEAMENT AND TONAL ANOMALIES, WEST HACKBERRY DOME AREA

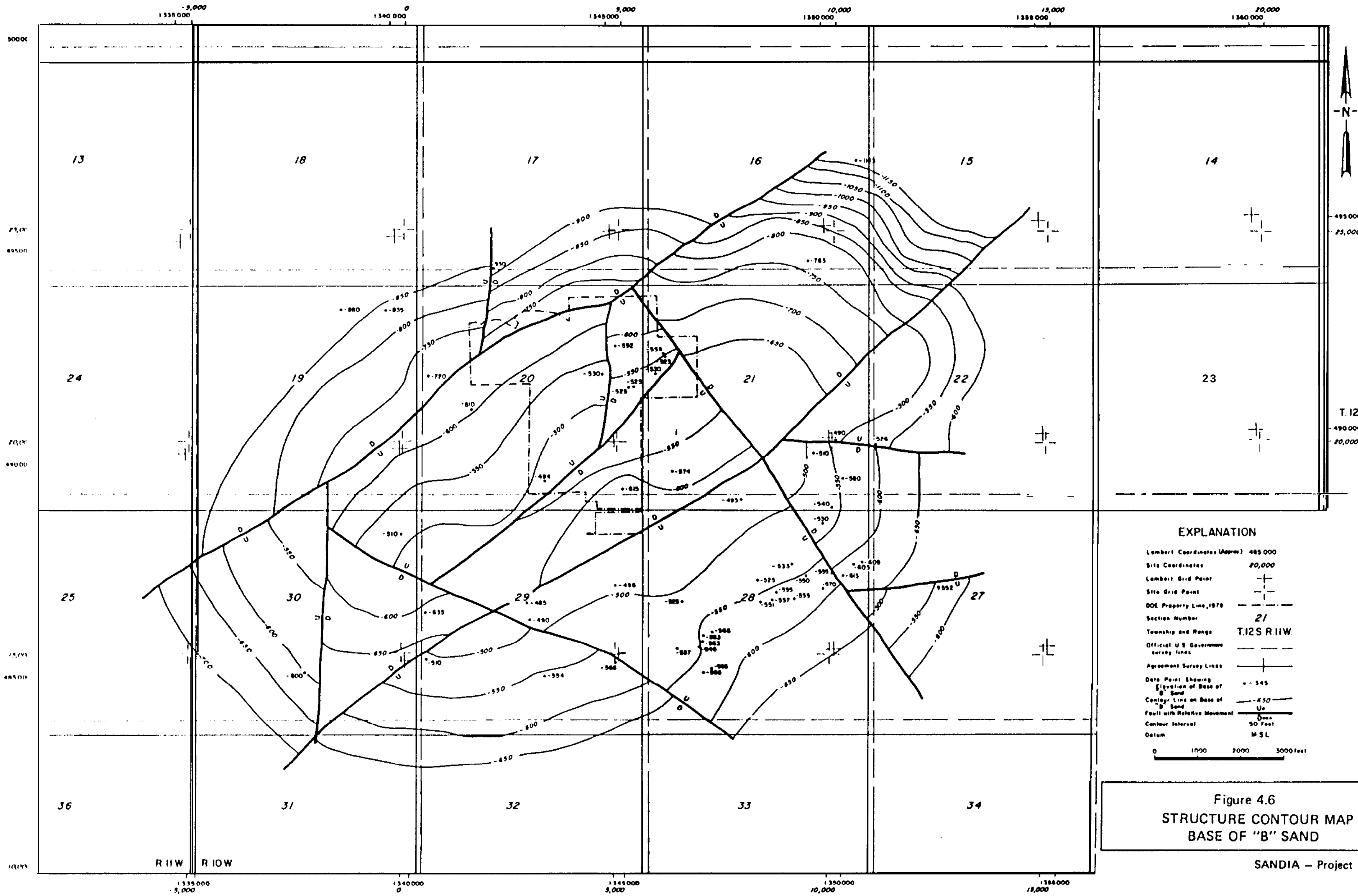


Figure 4.6
STRUCTURE CONTOUR MAP
BASE OF "B" SAND

SANDIA – Project No. 14620A

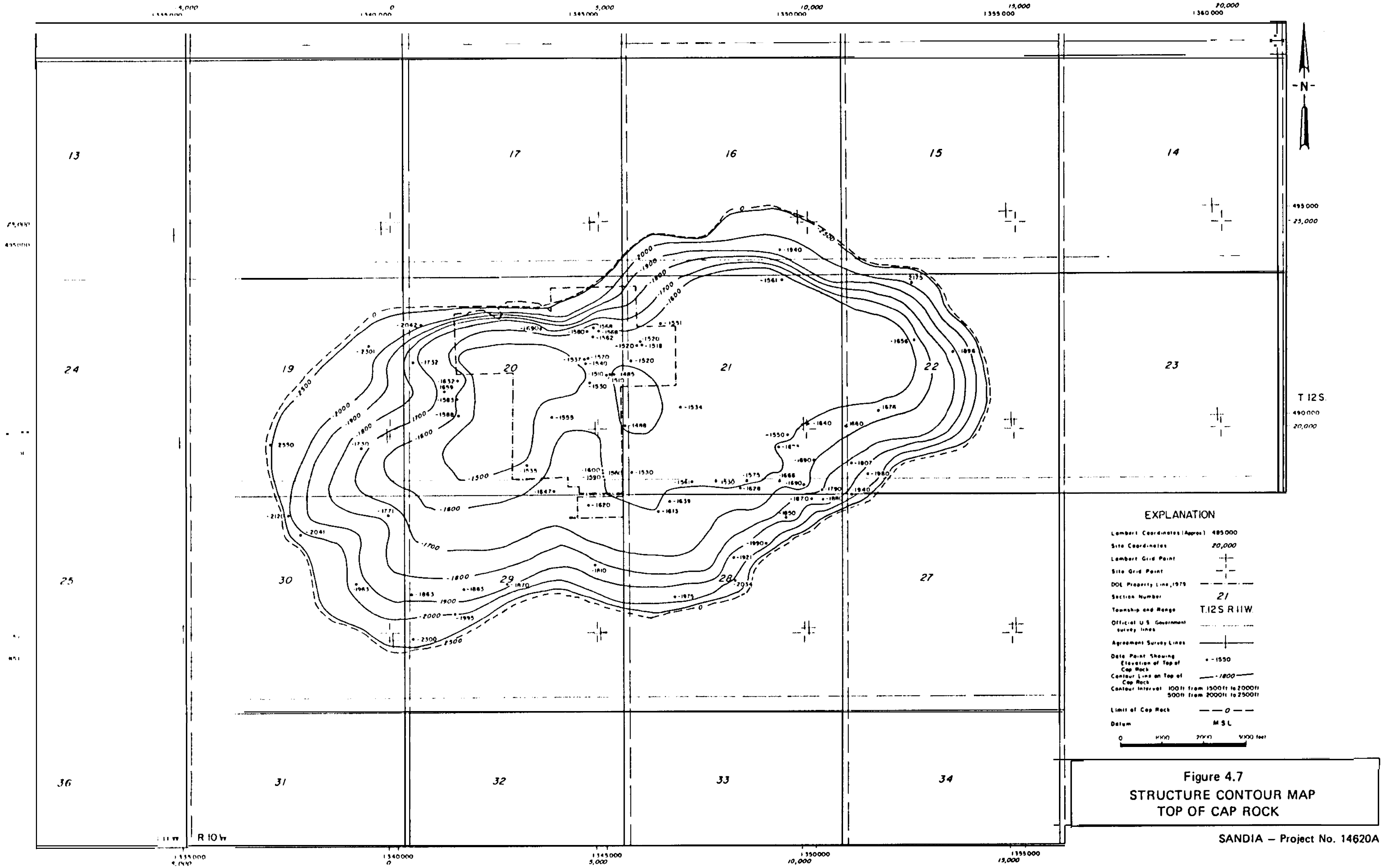


Figure 4.7
STRUCTURE CONTOUR MAP
TOP OF CAP ROCK

SANDIA – Project No. 14620A

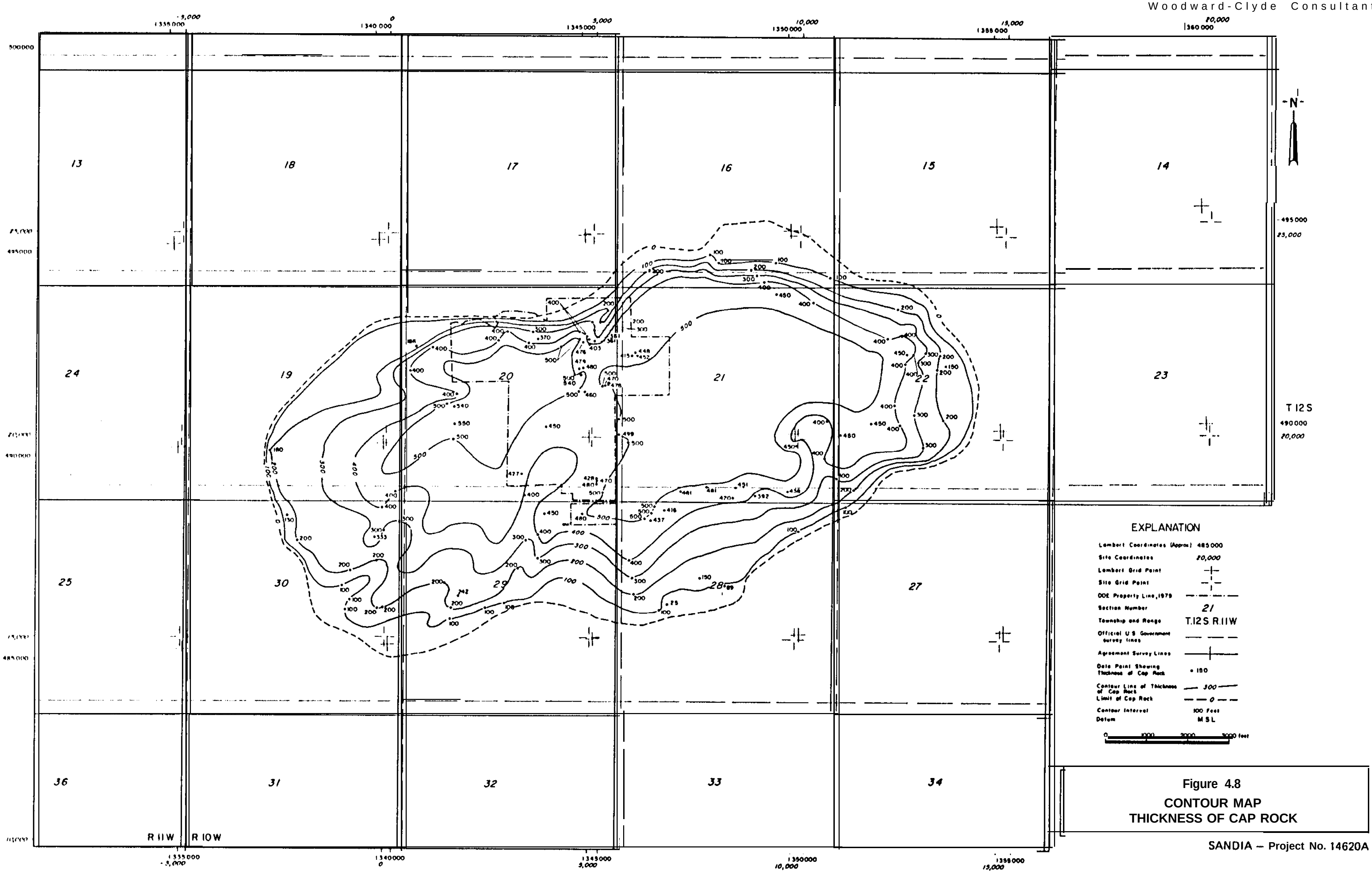


Figure 4.8

CONTOUR MAP
THICKNESS OF CAP ROCK

SANDIA – Project No. 14620A

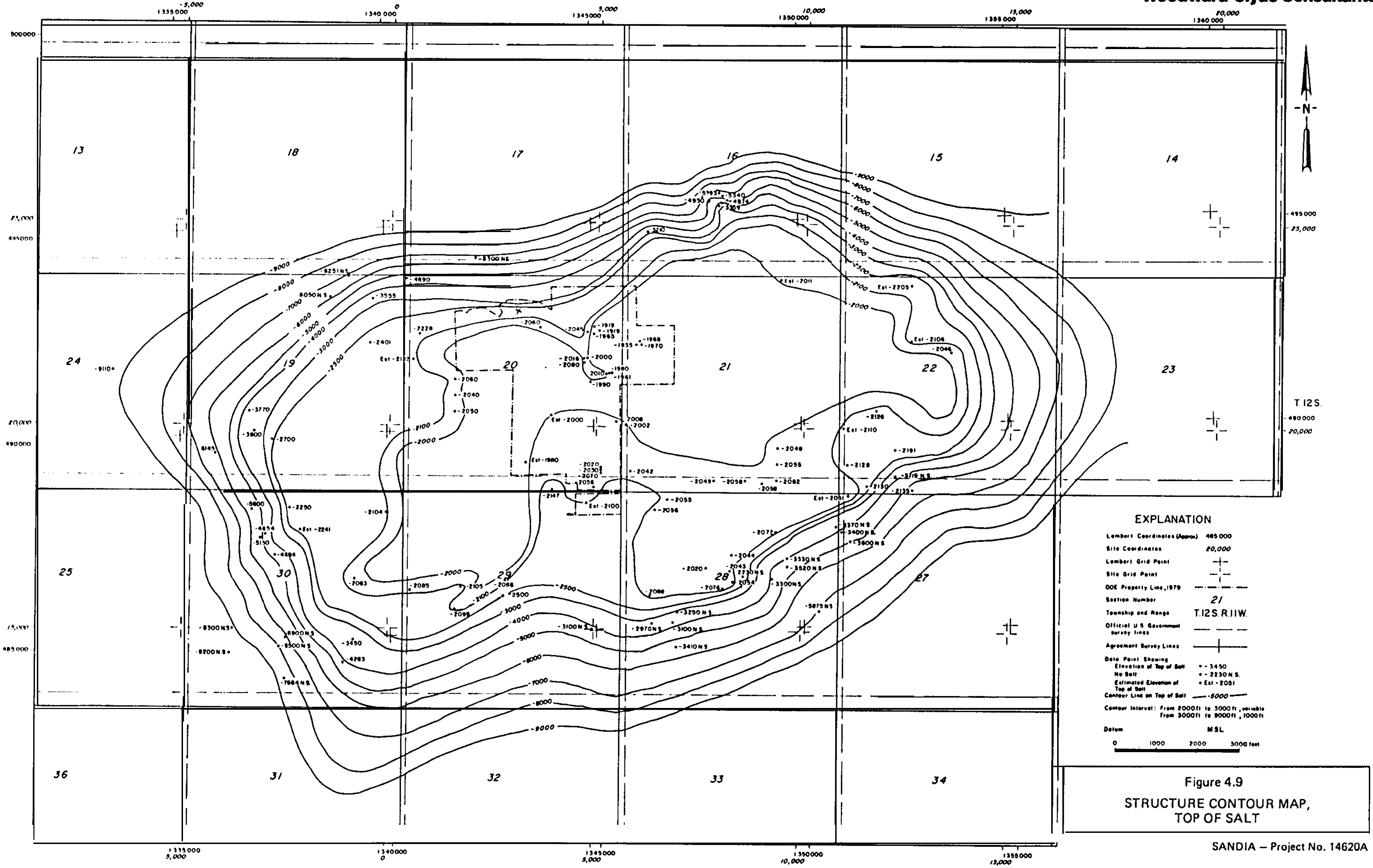


Figure 4.9

STRUCTURE CONTOUR MAP, TOP OF SALT

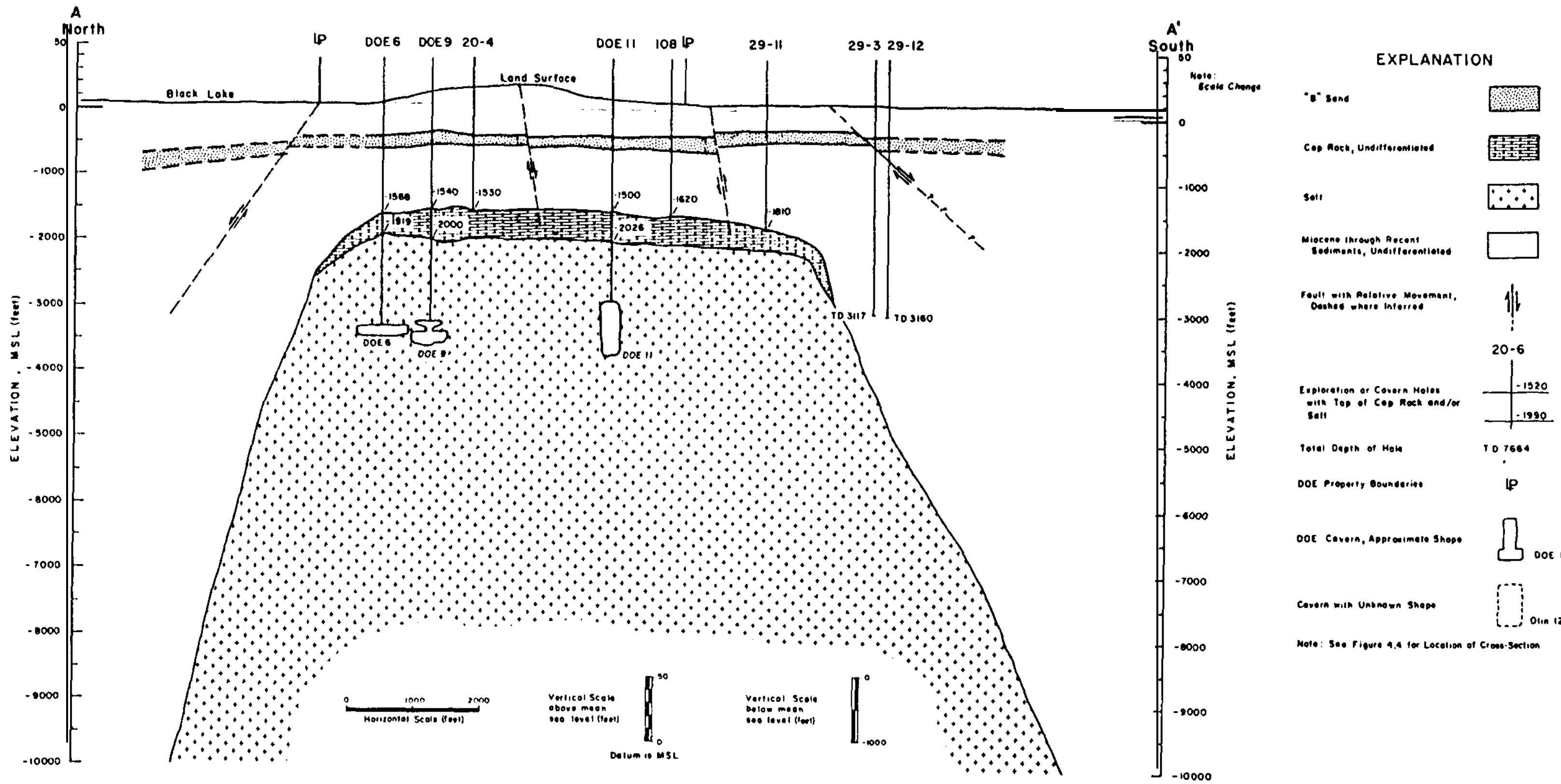


Figure 4.10

STRUCTURAL CROSS-SECTION A-A'

SANDIA – Project No. 14620A

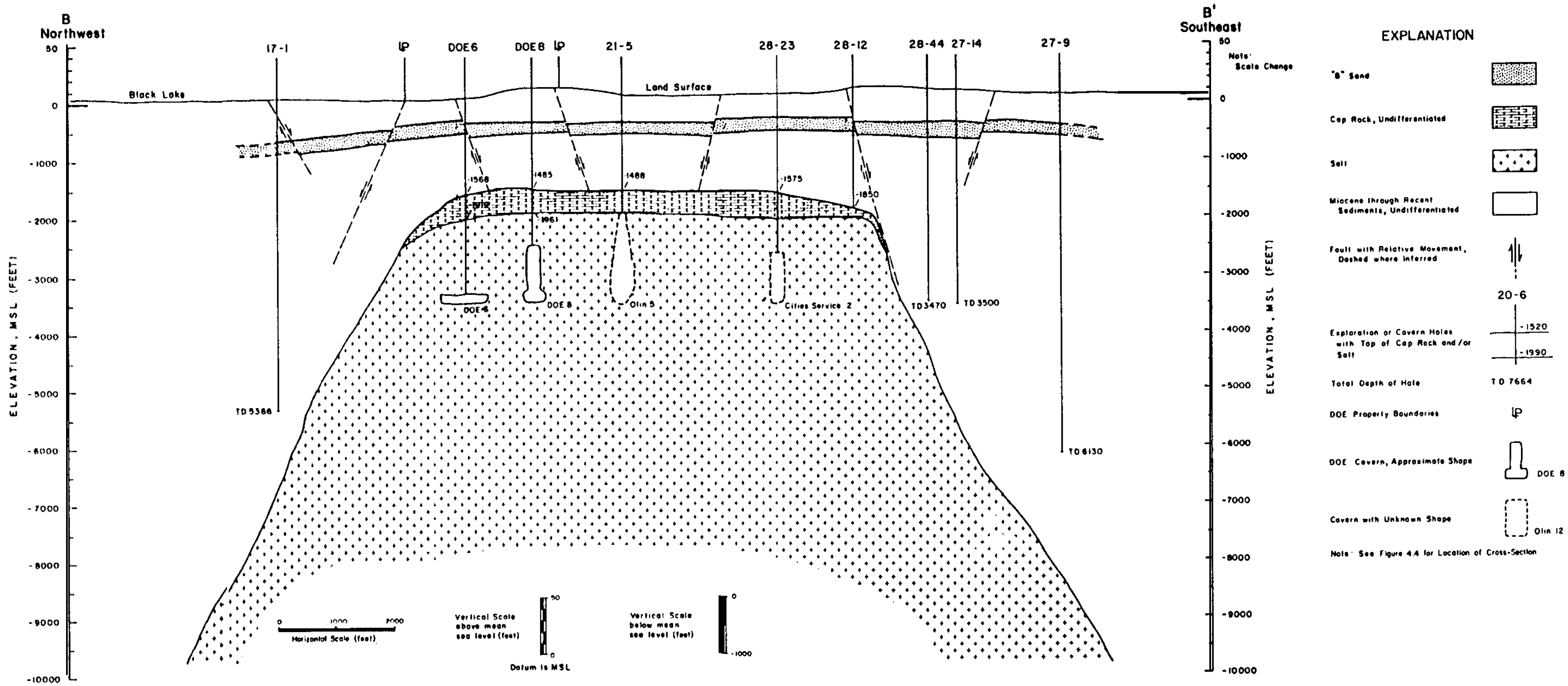


Figure 4.11
STRUCTURAL CROSS-SECTION B-B'

SANDIA – Project No. 14620A

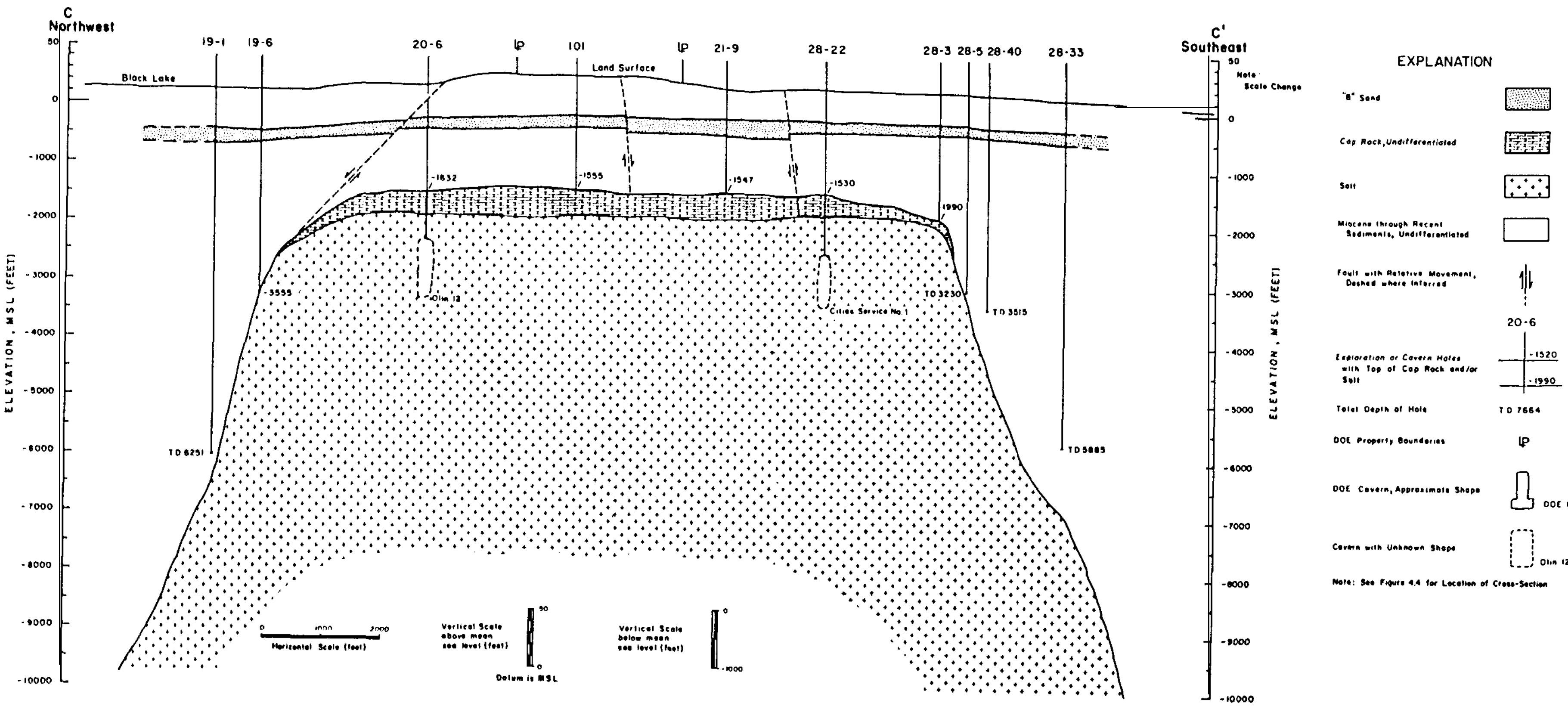
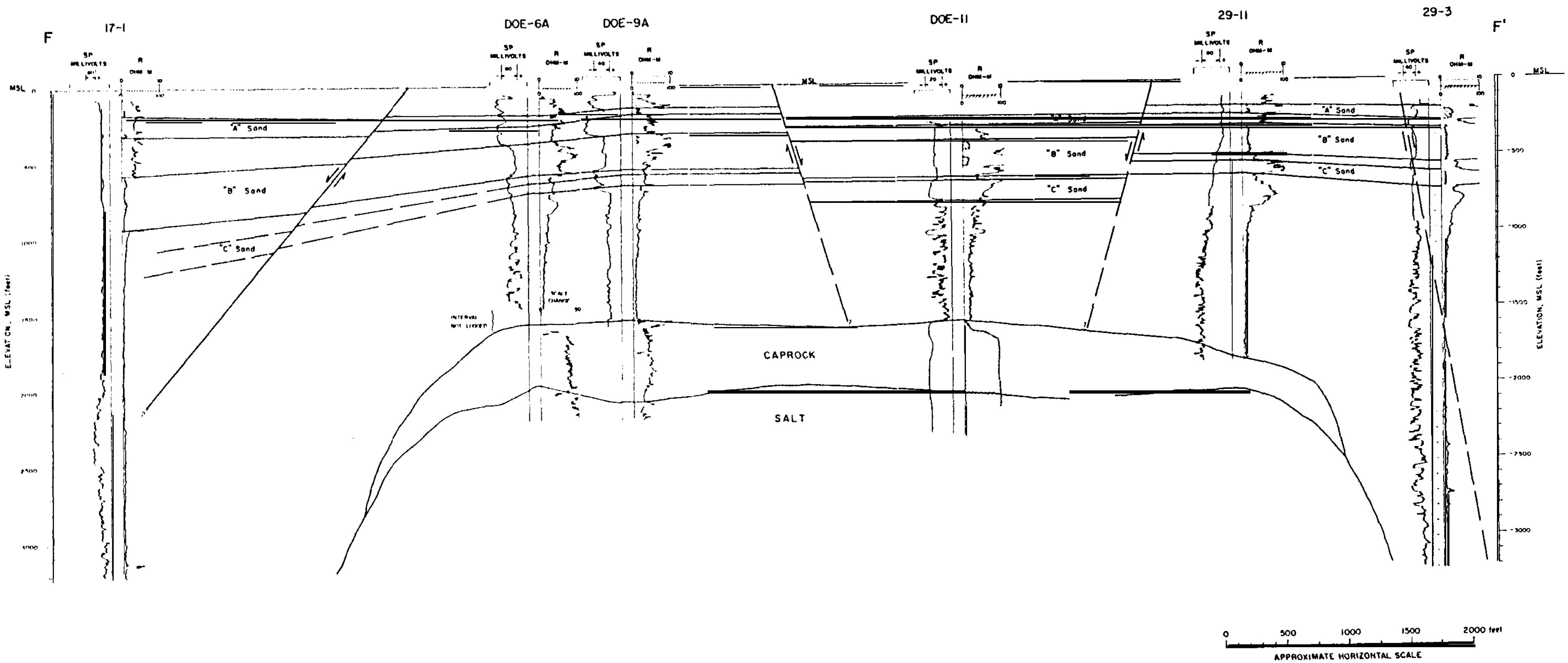


Figure 4.12

STRUCTURAL CROSS-SECTION C-C'

SANDIA – Project No. 14620A



EXPLANATION

Fault with Relative Movement, Dashed where inferred

Spontaneous Potential Log SP

Resistivity Log R

NOTE:
See Figure 4.4 for Location of Cross-Section

Figure 4.15

E-LOG CROSS-SECTION F-F'

SANDIA – Project No. 14620A

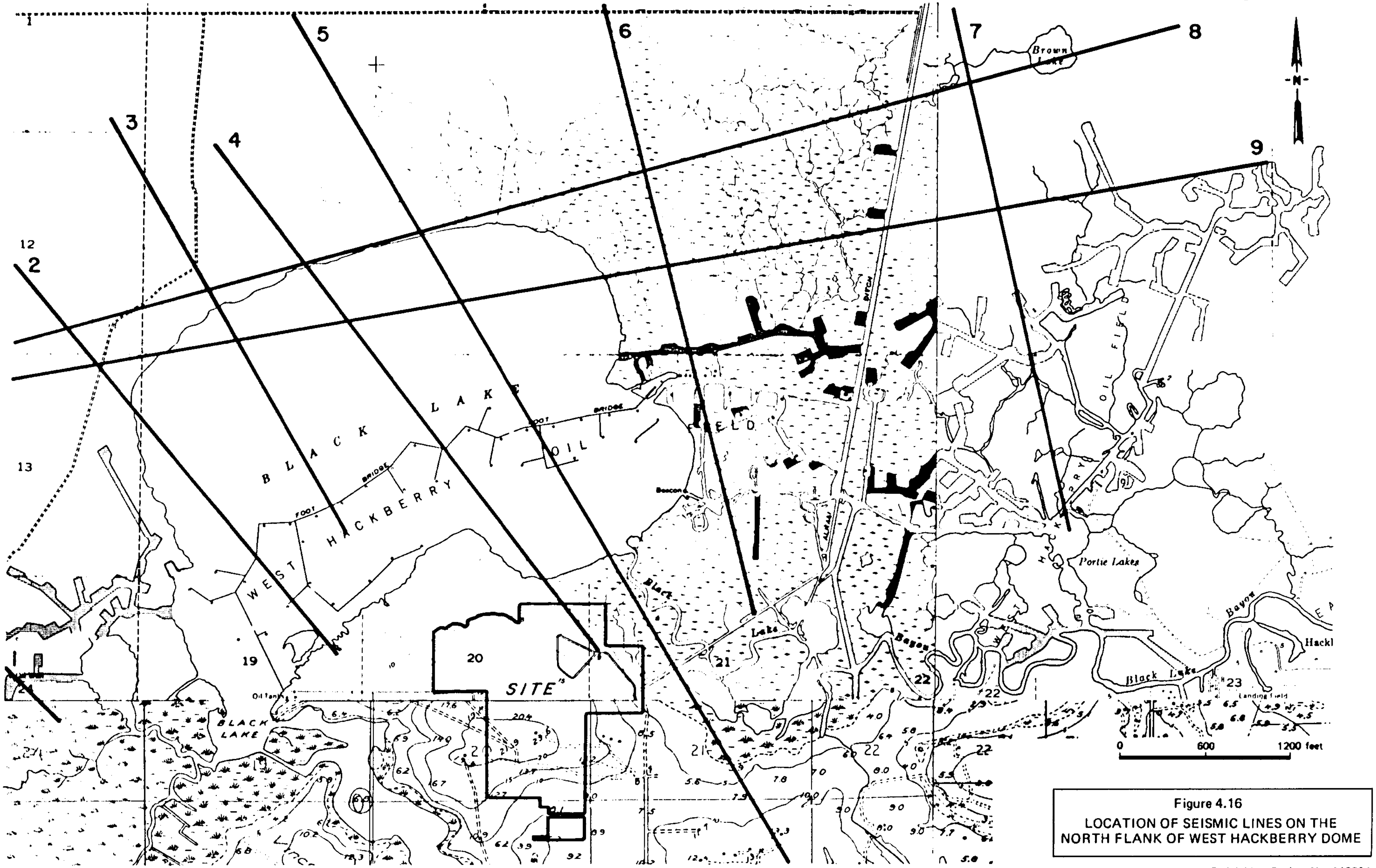
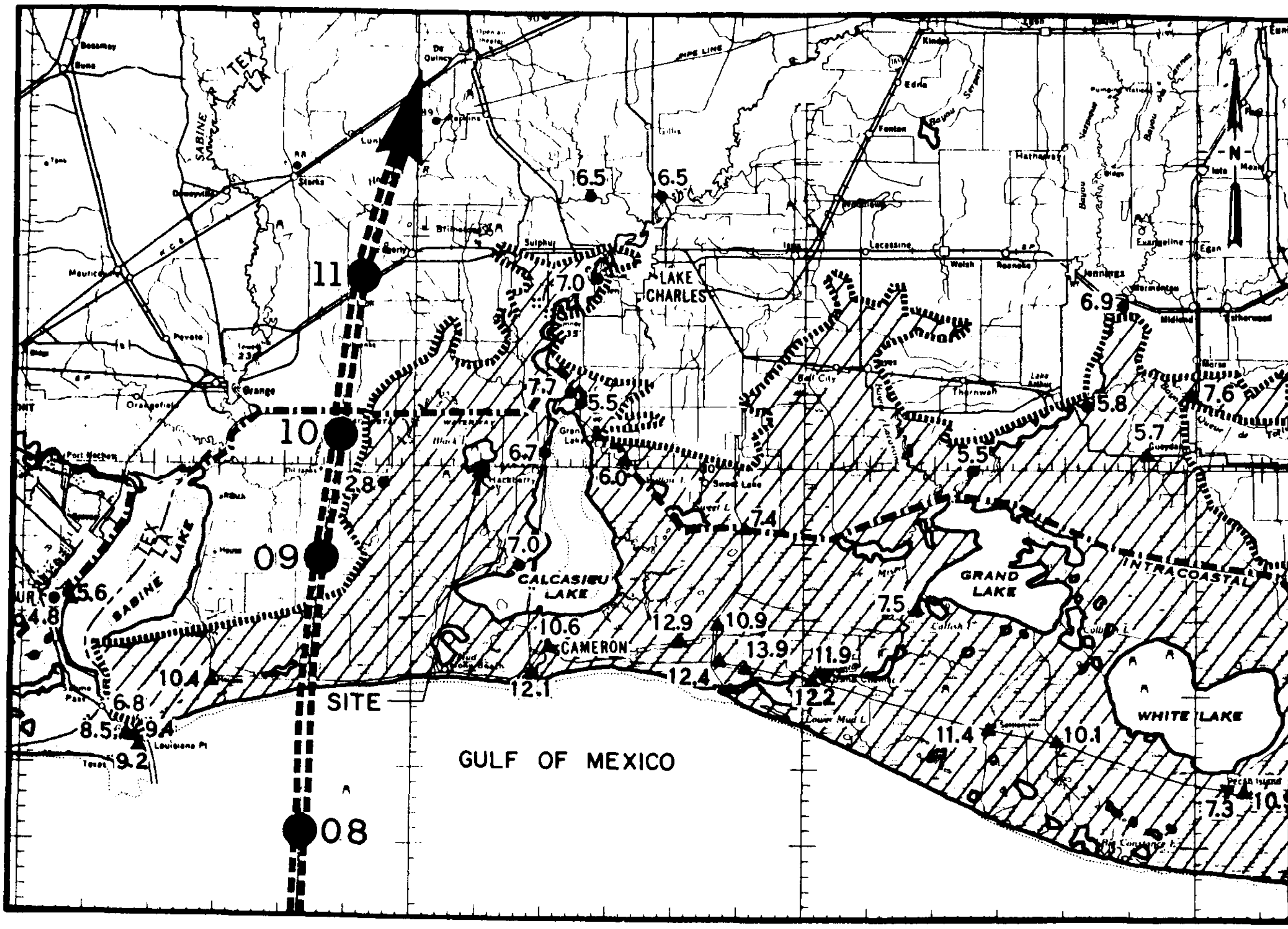


Figure 4.16
LOCATION OF SEISMIC LINES ON THE NORTH FLANK OF WEST HACKBERRY DOME



EXPLANATION

08 Time (Hours)

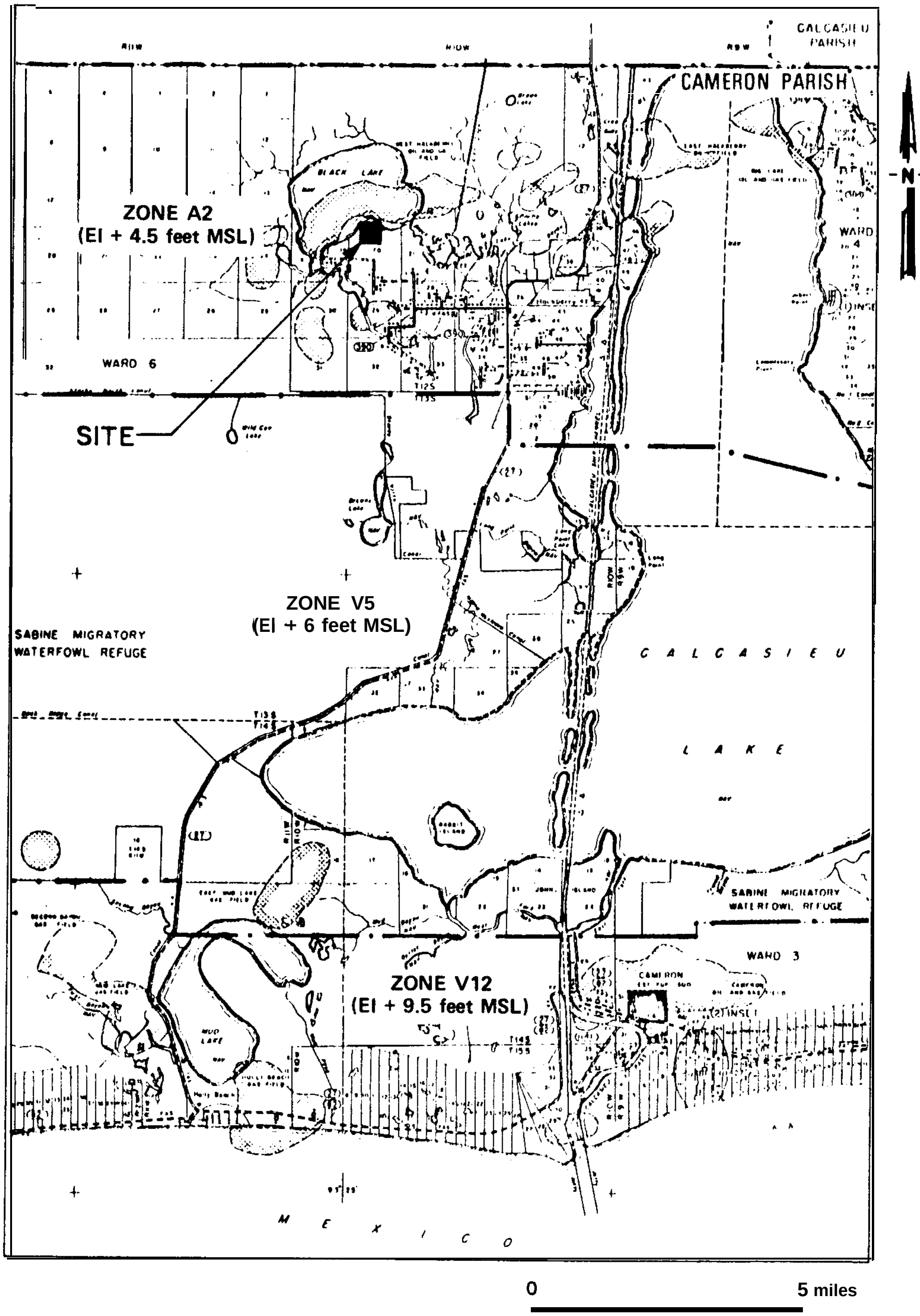
7.5 Surge height (Feet MSL)

Hurricane path

Source: Harris, 1958

Figure 4.17

HIGH WATER MARKS FROM HURRICANE AUDREY, 1957



EXPLANATION:

ZONE A: Area subject to 100-year flood-surge

ZONE V: Velocity Zone
Area subject to 100-year flood-surge

NOTE:

This map delineates the formal boundaries of the flood plain area having special flood hazards for the purposes of the emergency flood insurance program. It supersedes and replaces Map No. H&E 22 023 0000 02 which temporarily designated the entire community as an area of special flood hazard.

Adapted from Federal Insurance Administration, Cameron Parish Map No. H 07, dated Sept. 4, 1970.

Figure 4.18
FEDERAL INSURANCE ADMINISTRATION
FLOOD HAZARD MAP

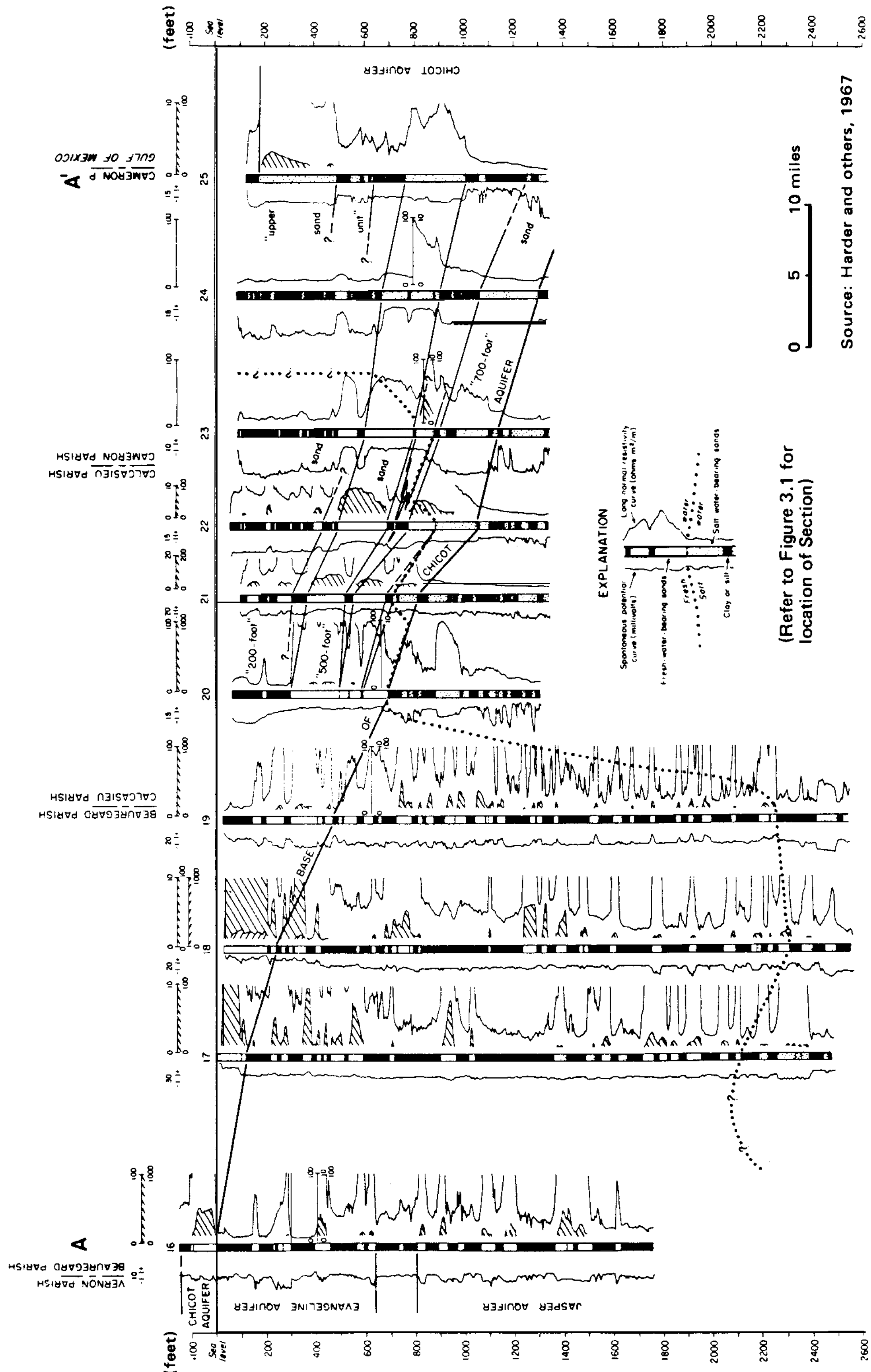
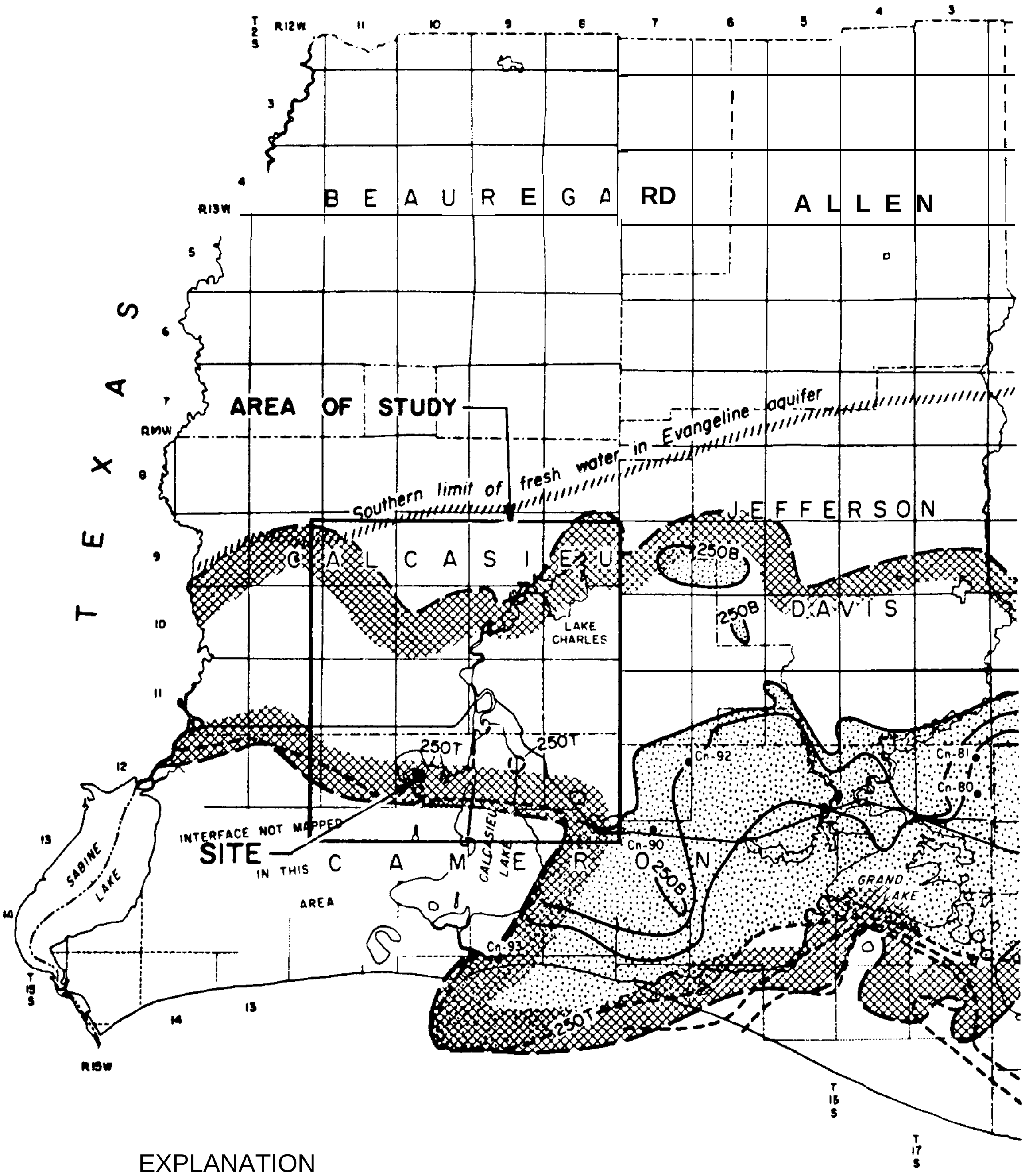


Figure 4.19

GEOHYDROLOGIC SECTION FROM NORTHERN BEAUREGARD PARISH TO SOUTHERN CAMERON PARISH, LOUISIANA



EXPLANATION

250B / 250T — Chloride concentration, in parts per million, on Bottom (B) and on Top (T) of "Upper Sand Unit"

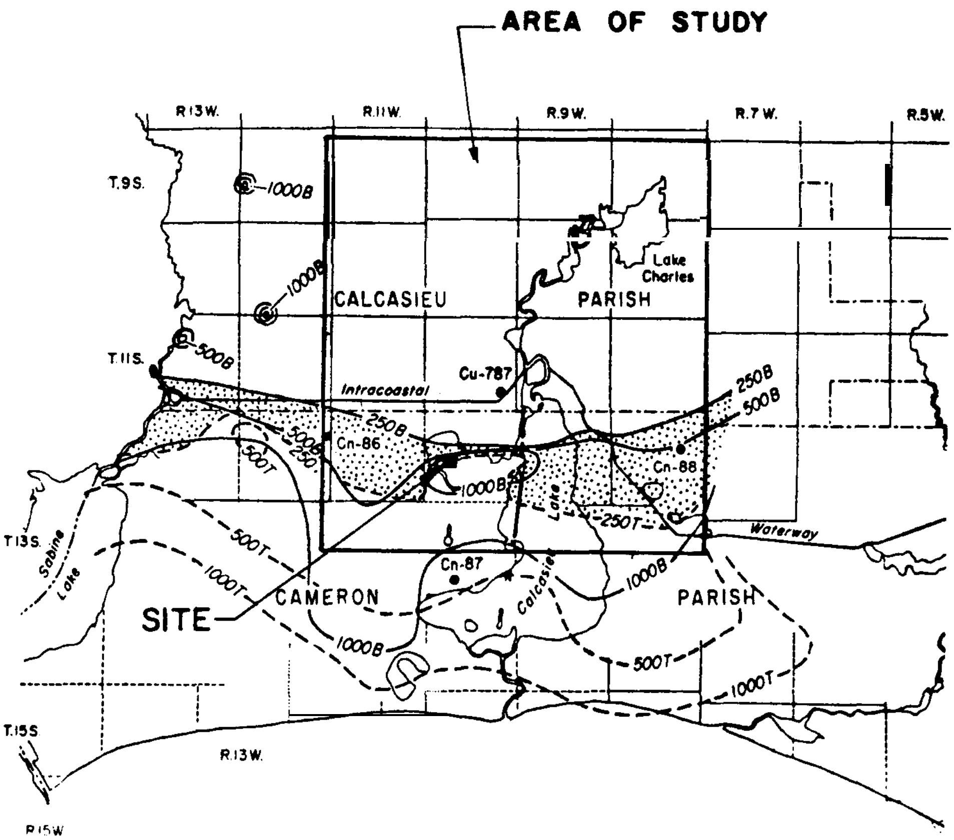
North and south limits of 250 ppm chloride in Chicot-Atchafalaya Aquifer

SM-57 — Salt-water monitor well and number

Source: Harder and others, 1967

0 5 10 15 20 25 30 miles

Figure 4.20
FRESH/SALT-WATER INTERFACE IN THE CHICOT-ATCHAFALAYA AQUIFER AND IN THE "200-FOOT SAND" OF THE CHICOT AQUIFER, SOUTHWESTERN LOUISIANA



EXPLANATION

250B / 250T — **Chloride concentration, in parts per million, on Bottom (B) and on Top (T) of sand**

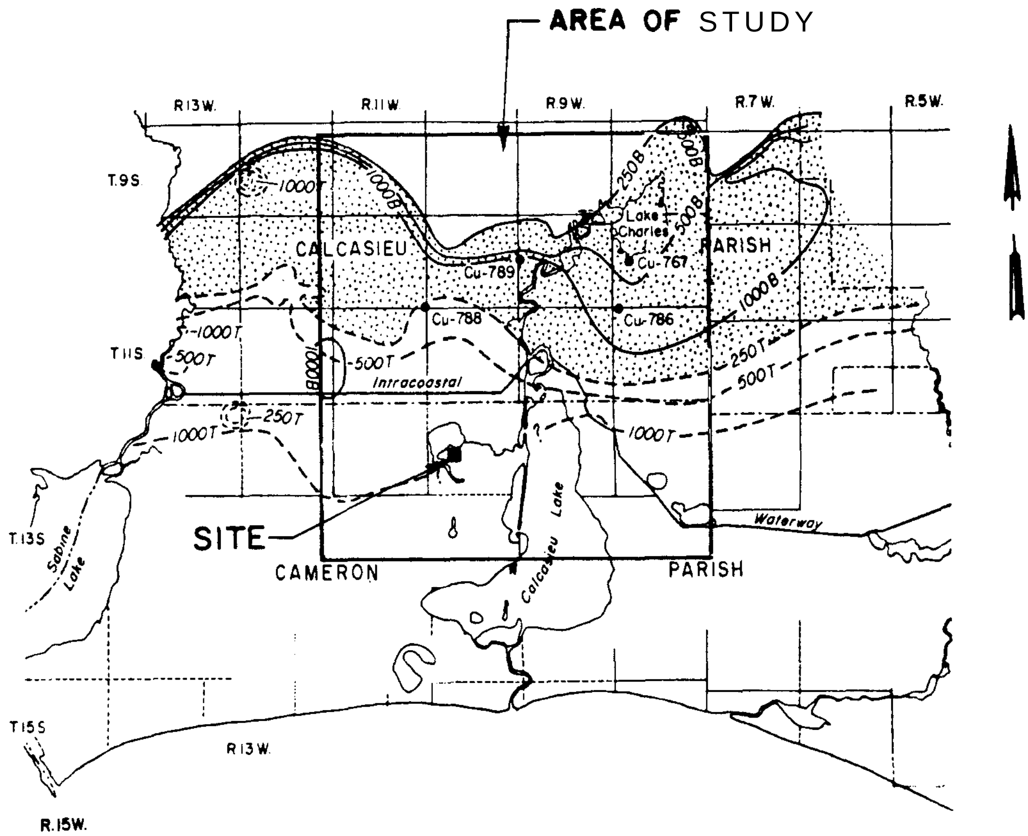
Cn-87 ● — **Salt-water monitor well and number**

Source: Harder and others, 1967

0 6 12 18 24 30 miles

Figure 4.21

FRESH/SALT-WATER INTERFACE FOR "500-FOOT" SAND OF THE LAKE CHARLES AREA



EXPLANATION

250B
250T

Chloride concentration, in parts per million, on Bottom (B) and on Top (T) of sand

Source: Harder and others, 1967

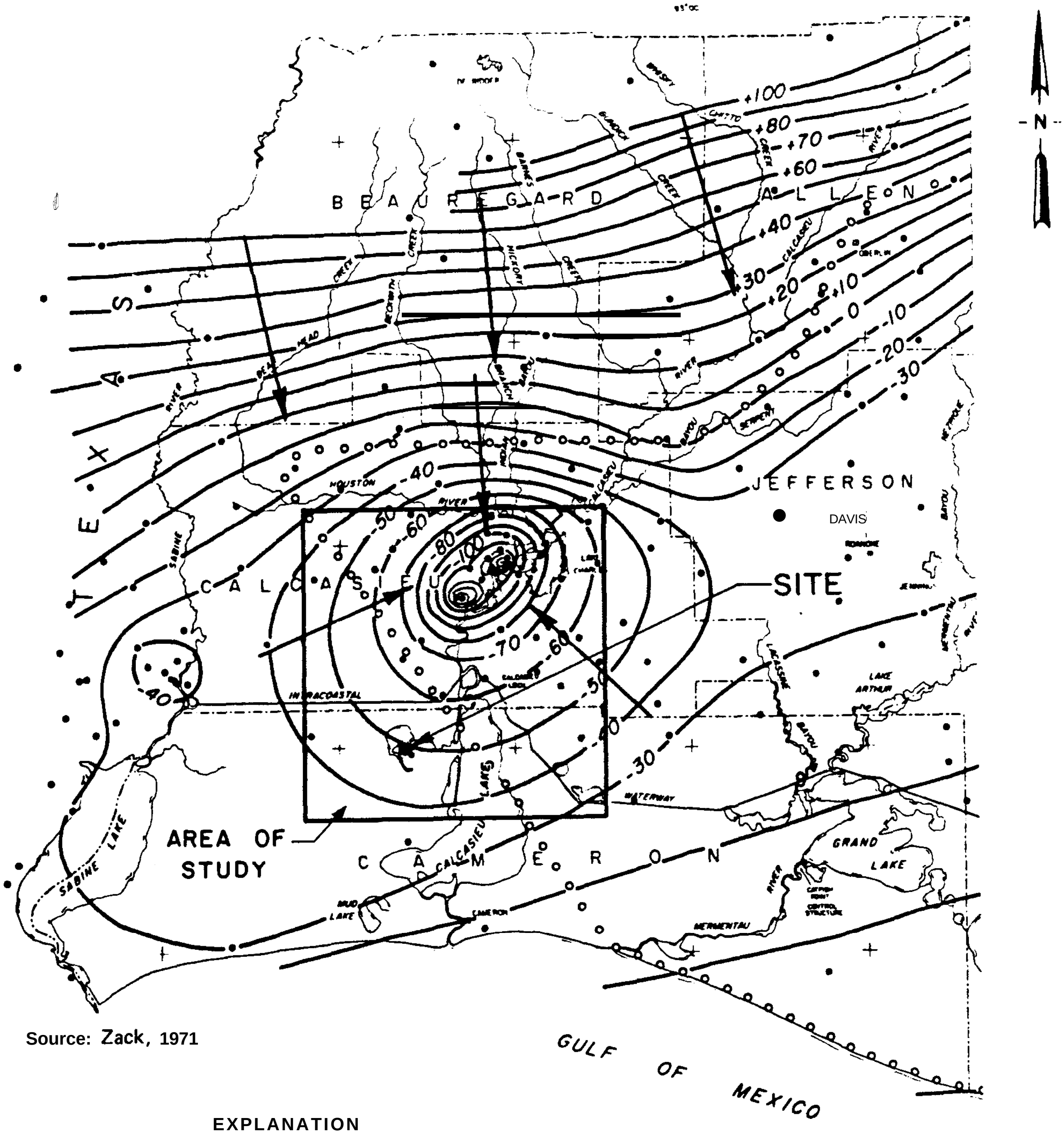
Cu-767

Salt-water monitor well and number

0 6 12 18 24 30 miles

Figure 4.22

FRESH/SALT-WATER INTERFACE FOR "700-FOOT" SAND OF THE LAKE CHARLES AREA



Source: Zack, 1971

EXPLANATION

-20 Piezometric contour for altitude of water levels in wells. Contour interval is 10 feet. Datum is mean sea level.

. Well used as control point.

0 0 0 Approximate boundary of rice-growing area

→ Direction of groundwater flow

0 10 20 30 miles

Figure 4.23
ALTITUDE OF PIEZOMETRIC SURFACE IN THE CHICOT AQUIFER IN SOUTHWESTERN LOUISIANA, SPRING 1970

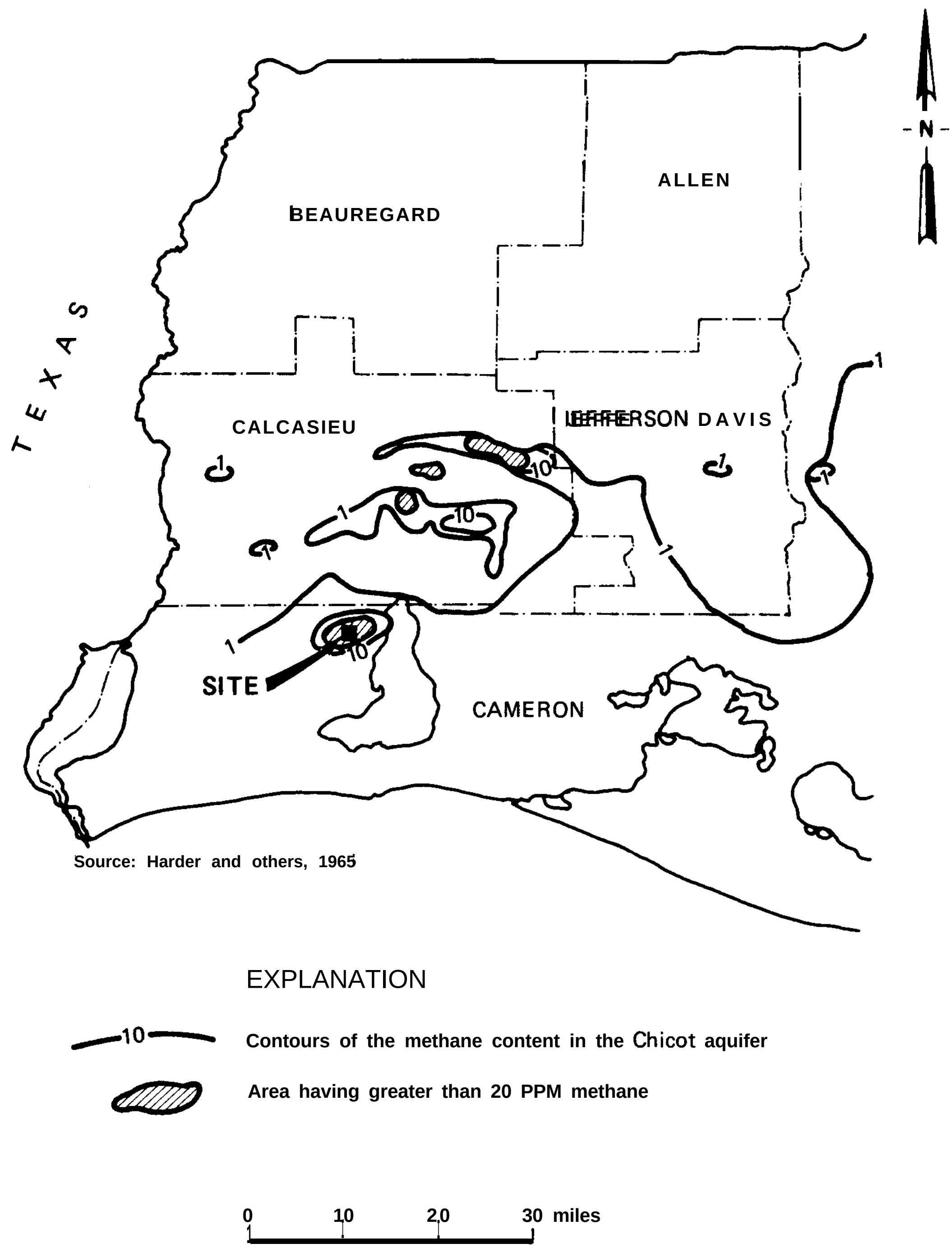


Figure 4.24
DISTRIBUTION OF METHANE IN GROUND WATER OF SOUTHWESTERN LOUISIANA

5.0 GEOLOGY OF THE CAP ROCK

This section presents a general discussion of the composition and origin of the cap rock and a discussion of the available data regarding the cap rock at the West Hackberry SPR Site. A discussion of the history of exploration and exploitation of the site area, including the cap rock, is presented. The locations of the wells mentioned in this section are tabulated in Appendix A and are shown on Figure 4.4.

5.1 GENERAL DISCUSSION OF CAP ROCK

The name "cap rock" has been used to define a variable mass of lithotypes that is found on the top, and commonly on the sides, of many salt domes. Of 329 known salt domes in the Gulf Coast region, 181 have cap rock. The average thickness of the Gulf Coast cap rock has been estimated at between 300 and 400 feet[32]. However, thicknesses of more than 1,500 feet are known to occur over some domes[119]. The presence of cap rock over a dome does not appear to be directly related to the depth of the dome because cap rock occurs over both deep and shallow domes. Nevertheless, cap rock is more likely to be present and to have a more pronounced thickness over shallow domes"'.

Anhydrite is the dominant material found in cap rock, although gypsum, carbonates (calcite and dolomite), and sulfur are present in lesser amounts. Mineralogical zoning (or layering) of cap rock is found in some domes, although this is not the general case. Where zoning or layering has occurred, the sequence typically consists of a calcite zone on top, an intermediate or transitional zone composed of gypsum and/or sulfur, and an anhydrite zone at the base (Figure 5.1)". The contacts between the various zones typically are gradational; the zones themselves are very irregular in shape and extent.

A zone of hard, indurated sediments that have been secondarily cemented by silica, calcite, or occasionally, pyrite is associated with many domes. *Where* present, these indurated sediments, commonly called "false cap rock," immediately overlie the cap rock or salt where cap rock is absent[32]. False cap rock may grade into the true cap rock, or fragments of it may be found within the true cap rock[90].

Originally, two principal processes were considered to interact in cap rock accumulation: residual accumulation and secondary alteration[23,109]. For the residual accumulation process, ground water, which may be undersaturated with respect to salt, dissolves the salt and leaves behind the less soluble residues, mostly anhydrite. Secondary alteration is considered responsible for the formation of many of the minerals found in the cap rock. Minerals, such as gypsum ($CaSO_4 \cdot 2H_2O$), calcite ($CaCO_3$), and sulfur, are thought to derive from the alteration of anhydrite ($CaSO_4$). Carbon, required for the formation of carbonates, is derived from the oxidation of hydrocarbons. Free sulfur and hydrogen sulfide (H_2S) result from the action of sulfate-reducing bacteria (Desulfovibrio desulfuricans), which are found associated with petroleum.

The great thickness of the accumulated anhydrite and the presence of exotic minerals such as celestite ($SrSO_4$) in the cap rock are difficult to explain when only these two processes are considered. Celestite is found in minor quantities in Texas and Louisiana; however, it constitutes approximately 90 percent of the cap rock of some domes in Mississippi. Celestite is not present in the salt's less soluble residue and therefore cannot be explained by residual accumulation[119]. Secondary alteration also is unlikely to produce such large accumulations[119].

Because anhydrite constitutes only about 5 percent of the total source salt in the Gulf Coast, an incredible thickness of salt would be required to obtain the thick anhydrite accumulations observed in some cap rock[119]. As a variation to prevailing theories, a "modified precipitation in place" theory has been proposed in which part of the anhydrite in the cap rock derives from the dissolution of salt from the flanks of the dome by ascending ground waters that are undersaturated with respect to halite[119]. The theory differs from an earlier model in that upward-moving ground water acts on the flanks of the dome, as well as on the top. Ground water of "low" salinity occurs at depths of 8,000 feet or greater in geopressured sediments in the Gulf Coast region. Also, clay "sheaths" occurring near the flanks of some domes may act as semi-permeable membranes through which ground waters are "desalted" by osmotic exchange. Other constituents, such as strontium, which are found in the cap rock but not in the salt, are picked up by water moving through sediments before and after dissolution of the salt. Thus, this model provides a plausible explanation for cap rock concentrationllg.

5.2 CAP ROCK GEOMETRY AND STRUCTURE AT WEST HACKBERRY

A well-developed cap rock overlies, and is in direct contact with, the salt across the top of West Hackberry dome. The thickness of the cap rock ranges from zero on the flanks of the salt to approximately 550 feet in the southwest quarter of Section 20 (Figure 4.8).

The top of the cap rock ranges in elevation from -1,500 feet on the top of the dome to approximately -2,700 feet on the flanks (Figures 4.7 and 4.8). In plan view, the cap rock has an elliptical shape, and reentrants occur near the minor axis, resulting in a shape somewhat resembling a peanut. These reentrants are even better depicted on the structure contour map of the top of the salt (Figure 4.9).

The cap rock is divided into two platforms (spires) on either side of the minor axis. The east platform occupies almost all of Section 21. The platform terminates at an elevation of approximately -1,600 feet and decreases to an elevation of -2,000 feet, forming a "terrace" shape. This terrace can be seen on cross sections B-B', C-C', D-D', and E-E' (Figures 4.11, 4.12, 4.13, and 4.14). The west platform of the cap rock is centered in Section 20. The platform falls off steeply to the north and more gently to the south; this is shown on cross sections A-A', B-B', C-C', and E-E' (Figures 4.10, 4.11, 4.13, and 4.14). A terrace found on the west side of this platform is illustrated on cross section D-D' (Figure 4.13).

The reentrants and terraces observed on the structure maps and cross sections appear to be related to faulting. Reentrants in the cap rock (Figure 4.7) closely approximate areas of faulting in the "B" sand (Figure 4.6). This is well illustrated in the northeast corner of Sections 20 and 28 (Figures 4.6 and 4.7). On cross section D-D' (Figure 4.13), a fault in the "B" sand corresponds to lineaments seen on the surface and to a terrace in the cap rock, illustrating a relationship between surface fault traces, faulting in the "B" sand, and the formation of terraces in the cap rock. However, further comparison of Figures 4.6 and 4.7 and cross sections A-A' through E-E' (Figures 4.10 through 4.14) indicates that many faults in the "B" sand are also expressed by structural irregularities in the cap rock.

The "peanut" shape of the cap rock and the resulting two platforms may suggest that the two sections of the dome have moved independently of one another, possibly in an episodic manner. Evidence for this type of movement has been observed in other salt domes of the Gulf Coast[54].

5.3 LITHOLOGY OF THE CAP ROCK

Information on the lithology of the cap rock of the West Hackberry dome is scarce. Thirty-four wells are known to have penetrated the cap rock; however, only 8 of the 34 yielded any information concerning lithology of the cap rock. For four of the wells (20-1, 20-3, 20-14, and 21-4), direct data are in the form of driller's logs; for two wells (DOE 7A and 7B), core samples were taken (included in core logging effort, Appendix D). Wells 20-6 and 20-7 have bulk density logs. In addition, several driller's logs that partially described the first 50 to 100 feet of the cap rock were located.

The driller's logs of wells 20-1, 20-3, 20-14, and 21-4 are of little use because vague, colloquial terms (such as "rock," "hard rock," and "lime rock") are used to describe the materials penetrated by the well bore.

The partial cores of cap rock from wells DOE 7A and 7B are composed of a finely crystalline, dark gray dolomite with anhydrite inclusions and stringers[122,123]. In well DOE 7A, a g-foot-thick section of anhydrite overlies the first occurrence of dolomite. Within the dolomite, cap rock in well DOE 7B, 10 to 15 feet of halite is present (as an inclusion(s) in the cap rock). A strong H_2S odor was present with the halite.

The bulk density log of well 20-6 indicates that the cap rock is composed of two principal units. The upper unit is approximately 250 feet thick and comprises an alternating sequence of higher and lower density materials, each approximately 8 to 9 feet thick. The higher density material has a bulk density of 2.95 to 2.97 g/cc. The lower density material has a bulk density of 2.80 to 2.85 g/cc. These bulk densities are in the range of anhydrite and dolomite, respectively. (Pure dolomite and pure anhydrite have specific gravities [densities] of 2.85 g/cc and 2.89 to 2.98 g/cc, respectively).

The lower unit is about 150 feet thick and is composed of an alternating sequence of materials of varying thickness. The high density material has a bulk density of 2.90 to 2.96 g/cc and the low density material has a bulk density of approximately 2.60 to 2.69 g/cc. The higher density material is in the range of anhydrite; however, difficulty arises in assigning a lithology to the lower density material. The density is too low for limestone (calcite, specific gravity 2.72). Sandstone falls within this range, but sandstone does not fit the models of cap rock lithologies. This low density material may be a combination of salt with either dolomite or anhydrite, or it may represent a porous dolomite produced by dolomitization (the process by which limestone is altered to dolomite, resulting in a 12 to 13 percent increase in porosity)60.

The bulk density log of well 20-7 also indicates two units in the cap rock. The upper unit and the lower unit are each approximately 250 feet thick. The bulk density of the high-bulk material in the upper unit is 2.75 to 2.78 g/cc, while the bulk density of the low-bulk material is 2.69 to 2.71 g/cc. The lower unit has a high density material between 2.77 and 2.79 g/cc and a low density material between 2.70 and 2.73 g/cc. The apparent specific gravities of the units in well 20-7 do not readily fit any of the presumed rocks in the cap rock, although the layering is consistent with well 20-6. On that basis, it is presumed that the log of well 20-7 was in error due to lack of calibration.

A considerable number of holes have been drilled into the site cap rock during sulfur exploration (Section 5.5). Two test holes, Hackberry Oil Lacy Nos. 1 and 2, each reported about 11 feet of sulfur near the top of the cap rock. These wells are located in the southwest quarter of Section 22 (only location given: not included on listing, Appendix A). Inasmuch as no sulfur mining was ever conducted at West Hackberry, it is inferred that little or no additional sulfur was encountered in the cap rock.

Driller's logs of several wells, which presumably penetrated the upper 50 to 100 feet of cap rock, have indicated the presence of a false cap rock[32]. Several driller's logs have intervals described as "hard sand, containing pyrites," "heavy shale," and "broken rock," terms indicative of harder false cap rock (Section 5.1).

False cap rock may be present on top of the salt where cap rock is absent. Based on driller's logs and electric logs of wells 16-5 and 29-14, salt was encountered, but no cap rock. The driller's log did indicate the presence of a "hard sand containing pyrites." However, this harder material could also be part of the sheath (see Section 6.3 for description of sheath).

A false cap rock may also be responsible for apparent errors in picking the top of the cap rock. This is illustrated in wells DOE 11 and llA, which are very close, yet for which the picks of the top of the cap rock differ by 100 feet.

5.4 HYDROGEOLOGY OF THE CAP ROCK

Little is known of the hydrogeology, including the geochemistry of fluids, of the cap rock at the West Hackberry SPR Site. Driller's logs refer to numerous instances of broken rock, and at least one report of a cavity in cap rock where the rods dropped 8 feet[72]. An anomalous flow of methane has been reported, which also suggests moderately high porosity and permeability[37]. No potentiometric data of fluids in the cap rock are available. Given this lack of data, it is only possible to assume that the direction of fluid movement is controlled by the regional ground-water gradient at the depth of the cap rock.

Very little data are available on the geochemistry of the ground water in the cap rock. The ground water is believed to have high concentrations of salt (brine) and locally, high concentrations of both methane gas and hydrogen sulfide. As discussed in Section 7.2.4, both the methane and hydrogen sulfide represent potential hazards that need to be assessed and considered in the design and operation of the West Hackberry SPR facility.

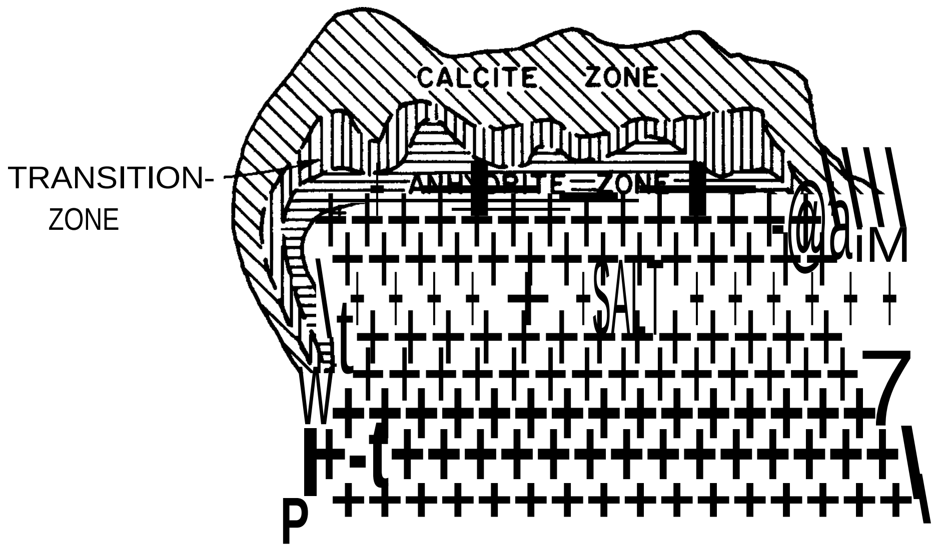
5.5 CAP ROCK EXPLORATION

Cap rock on Gulf Coast salt domes has been explored primarily for two items: hydrocarbons and sulfur. A number of Gulf Coast domes have yielded oil and gas from the cap rock where the fractural rock has served as a reservoir. Relatively high flows of methane have been noted at West Hackberry, but were uneconomical to develop. A relatively cheap way to mine sulfur from cap rock was developed at the Sulfur Mines dome near Lake Charles, Louisiana, and this provided the incentive for the sulfur companies to explore the cap rock of essentially all shallow domes. In most instances, it is difficult to differentiate between hydrocarbon and sulfur exploration holes, as these records are poorly defined. Test well permits are submitted as a permit to drill for minerals without specifically identifying the objective mineral. Minerals are reported only if the test is successful. Exploration companies would have been receptive to the economic recovery of minerals; however, the cap rock at West Hackberry dome was not productive.

Sulfur exploration at the West Hackberry dome may have begun as early as 1913 with the Gulf Refining Company Lacy No. 2 (22-7). However, it is likely that this well was an oil test and was drilled over the dome because of the lack of definition of the boundaries of the salt.

As there has never been any successful production of sulfur at West Hackberry, records are vague and the exact time that sulfur exploration began is uncertain. It is probably safe to assume that sulfur exploration had begun by 1927 when Freeport Sulfur and Union Sulfur drilled several test holes into the upper 50 feet of the cap rock. An early history of the salt domes of Cameron and Vermilion parishes do not differentiate between oil tests and sulfur exploration47. Therefore, it is assumed that the majority of the wells drilled on top and on the edges of the cap rock were drilled in the hope of finding commercial quantities of sulfur.

A rough criterion might be that those wells drilled to a depth of 1,500 to 2,100 feet were probably drilled in search of sulfur. Of the wells listed in Appendix A, Table A.2, 39 meet those criteria. There are no records to indicate that any significant amounts of sulfur were located, or that leaching operations were conducted in those wells. Records of two wells, Hackberry Oil Company Lacy Nos. 1 and 2, located in the southwest quarter, Section 22, indicated that about 11 feet of sulfur was encountered. There did not appear to be any follow-up to that exploration. (These two wells are not included in Appendix A because exact locations were not available). Sulfur exploration wells that only penetrated the upper cap rock should pose no threat to the stability of the cap rock or caverns but could be a path for contaminants to move up or down if improperly plugged.



Source: Taylor, 1938

Figure 5.1

SCHEMATIC CROSS-SECTION OF SALT DOME CAP ROCK

6.0 GEOLOGY OF THE SALT

6.1 INTRODUCTION

Numerous salt domes are present in the Gulf Coast region. The locations of known or probable domes are shown on Figure 6.1. Salt structures in the forms of anticlinal to ridge-like masses are also present in the region. These structures have a wide range of structural magnitude, height, and area1 extent, and they are thought to be caused by the rise of salt masses ("plugs" or "domes") from the deeply buried "mother salt," the Louann Salt.

The Gulf Coastal Plain is one of the classic areas in the world for salt domes. There are two general groups of domes: the coastal domes of Texas and Louisiana, and the interior domes of east Texas, north Louisiana, and the southern Mississippi embayment (Figure 3.2). The West Hackberry dome lies within the Gulf Coast salt dome basin.

Salt domes are classified according to the discordant or concordant nature of the adjacent and overlying beds relative to the salt. West Hackberry dome, as well as most other structures in the Gulf Coast Basin, are discordant structures. As they are the only type of structure significant to this study, the discussion is limited to discordant structures.

The discordant domes show penetration *or* intrusion of the salt and are termed diapirs or diapiric structures. They are produced by plastic intrusion of the salt through the overlying beds. As a result, complex faulting is usually associated with the salt plugs.

Many of the salt structures are associated with deposits of hydrocarbons, gypsum, sulfur, and/or halite: therefore, they have been the object of intense study for exploration and exploitation of minerals.

6.1.1 Origin Of Salt - The Louann Salt

The mechanics of salt precipitation in an evaporitic environment was discussed by Usiglio as early as 1849. In his work on the Mediterranean waters of France, he established that anhydrite ($CaSO_4$) precipitates after the volume of sea water has been reduced to about one-fifth. If volume reduction continues, halite (NaCl), followed by other minor salts, will precipitate.

Based on this salt precipitation sequence, the Louann Salt (composed mostly of halite) represents the halite stage, whereas the Castile Formation of west Texas (composed mostly of calcium sulphates) was deposited during the anhydrite stage[4*]. This concept was adopted as an explanation of the composition of the Louann Salt and was further developed to propose that the Louann evaporite basin, where salt perhaps started to accumulate as early as the late Permian, was formed and continued to subside at the same time as the adjacent Llanoria landmass[31].

Most authors agree that deposition of the Louann Salt kept pace with subsidence of the basin, which accounts for the thick sequence of evaporite material. Estimates of the total thickness of the Louann Salt vary from about 1,000 feet to as much as 15,000 feet, although 5,000 feet probably is a more realistic average figure[54,95]. Lesser amounts of anhydrite *are* found underlying the salt.

6.2 ORIGIN AND SHAPE OF SALT DOMES

Salt domes are abundant in the Gulf of Mexico region. A total of 329 domes has been reported, and it is possible that many others have not yet been identified'l'. The origin of salt domes has been the subject of speculation and controversy for many years. The most generally accepted theories on the origin of domes involve isostatic compensation due to material density differentials. Barton's theory of "isostatic downbuilding" postulates that the salt structure remains approximately constant in depth, whereas the overlying sediments subside around it as the overall basin subsides[5]. Salt is forced to flow horizontally towards a salt core due to the increased weight of overburden surrounding the core.

Nettleton's proposed explanation is consistent in many respects with Barton's ideasg2. His "fluid mechanical concept" postulates that upward intrusion of salt into the overlying sediments is due to the difference in density between the salt and the sediments. Salt has a specific gravity of 2.2; the specific gravity of sediments varies from 1.7 to 2.0 at the surface and 2.4 to 2.8 at depth. Salt can be deformed by shearing stresses of only 427 psi and calculations show that approximately 1,000 feet of sediments overlying the salt is needed to produce that stress and to initiate flow3rg5. Some authors emphasize the effect of overburden on temperature, because above 392OF salt behaves like a perfectly plastic materia13'. However, the visco-elastic properties of salt are such that it flows as a solid at low temperatures and pressures. These properties, combined with its low specific gravity, cause the salt to seek a level of density equilibrium or compensation.

Other authors suggest that the driving mechanism of salt intrusion is the result, at least in part, of tectonic controls. Bornhauser, for example, believes that the salt began to move downward on a sloping subsiding basin before initiating its upward migration[7].

In summary, two ideas are postulated for salt intrusion:

1) a compressive force due to tectonic causes in an erogenic environment; and

2) a buoyant force due to gravity differences in an isostatic environment.

The recent trend is to accept Nettleton's fluid mechanics mode, with a secondary role played by tectonics.

The influence of the density differential caused by thicker columns of sedimentary cover is illustrated by the increased abundance of salt domes in a gulf-ward direction. As depo-centers have migrated gulf-ward, the pressure differential has also increased in that direction and more salt piercement structures have resulted (Figure 6.2).

Salt structures occur in a variety of configurations, such as circular, ridge-like, tear drop, mushroom, and others. The genesis of a particular shape is complexly related to the interplay of various factors, such as thickness of mother salt bed, sedimentation rate, sediment thickness, faulting prior to and after salt intrusion, and resistance of the sediments to deformation. In most cases, it is not possible to relate form to origin in a cause-and-effect manner. However, the larger-scale salt structures (shown in Figure 6.3) have a direct relationship to thickness of the Gulf Coast sediments. Non-piercement structures are more abundant in the landward sections where the overlying sediments are relatively thin. Piercement and salt ridges predominate farther to the south where a thicker overlying sedimentary section exists.

Tubular masses that protrude from salt ridges are known as spines. These are secondary features, or apophysis, that develop from the .main structure (the salt ridge) and extend upward, piercing through the overlying sediments. West Hackberry and East Hackberry domes form spines from such a salt ridge or salt anticline (Figure 6.4).

6.3 FAULTING ASSOCIATED WITH SALT STRUCTURES

Faults and other fractures are found in association with most salt domes and other salt-controlled structures. Some domes, such as the Mallalieu dome in Mississippi, have no related major faulting; other domes, such as the Anahuac dome in Texas, exhibit a very complicated fracture pattern (Figure 6.5)32~g1.

Few reports of faulting within salt masses have been documented in the literature. Most reports of faulting associated with salt domes are related to overlying or adjacent sediments. Faults that are reported in salt masses are from salt mines where direct visual observations can be conducted. Thus, the lack of reported faulting within domes is more likely due to the type of data available (drill hole data, where correlation is difficult versus direct visual observations).

Faults associated with salt structures are either exterior faults or interior faults. Exterior faults are those that affect sediments over or adjacent to salt structures and may be regional or local in extent. Interior faults are those that affect the salt mass itself and may be present along boundaries or within the salt structure.

Exterior Faulting - The patterns of exterior faulting associated with salt structures include offset, radial, graben and, less commonly, horst structures over or adjacent to the domes and tangential, peripheral, and regional faults away from the dome (Figure 6.5)?2~gofl120. Most of these faults are produced by the upward movement of the salt plug that causes deformation of the surrounding sediments. Halbouty suggests that faults of regional extent (growth faults) probably preceded the growth of individual salt domes but may have been initiated by regional salt swells[32].

In addition to development of faults above and adjacent to piercement structures, the development of salt structures, such as in the Lake Calcasieu area, may have been accompanied by circular collapse faulting (Figure 6.6)lo6. The formation of these features is illustrated in Figure 6.7. Where large amounts of salt movement takes place (as in the development of the multiple piercements of the Hackberry area), a basin is created where the salt was withdrawn (Step 1, Figure 6.7). Collapse of overlying sediments into the salt withdrawal area, accompanied by the adjoining rise in salt, causes tensional or torsional stresses. These stresses are relieved by normal faulting into the center of the basin (Step II, Figure 6.7). Continued rising of salt masses establishes a repetitive cycle of collapse and withdrawal, forming a circular system of collapse faults (Step III, Figure 6.7). Development of the Hackberry ridge was probably strongly influenced by the Lake Calcasieu collapse structure, although the collapse faults do not directly affect the West Hackberry SPR Site (Figure 6.6).

<u>Interior Faulting</u> - Many researchers intuitively believed that the salt stocks moved in a single mass. However, mapping of salt stocks, both in this country and in Europe, have shown that the salt adjusts plastically to the particular conditions of the individual dome[3,54,89,103]. It has been recognized that various parts of the salt might move in a series of unit cylinders, called spines, with each moving at a separate speed

and creating interior shear zones between the units. These shear zones between the separate spines have received considerable attention,.particularly in the last 20 years.

External shear zones are defined as the clay-like gouge zones bordering the salt dome, including the shale sheath caused by the diapiric intrusion of the salt mass through the sediments (Figure 6.8)35t4g. The salt also often shows signs of shearing at the edge of the salt stock4. Kupfer has measured shearing at least 500 feet into the salt stock in the Weeks Island Mine. He further suggests that the combined shale-salt shear zone in most salt stocks would be approximately 1,000 feet wide, and locally, could be up to l/2 mile wide[53,54].

Boundary shear zones include that interval of shearing between salt spines where some of the shale sheath is caught between the two salt masses (Figure 6.8). Other parts of the boundary between spines include areas where salt is in contact with salt. These salt-to-salt shear zones are called internal shear zones (Figure 6.8). They are often transitional to the boundary shears and to the salt sheaths, except that all the material involved is salt.

Shearing in four salt mines in Louisiana was documented between the spines and the discontinuities within and along the boundaries of the spines and the salt stock55f156. In the Avery Island Stock, a boundary shear zone has been mapped for 3,500 feet, cutting across the salt stock in an arcuate pattern that divides the salt stock into two parts. The zone is typified by mixed rock units of salt, sand, and shale, 6 to 20 feet thick. The shear zone contains considerable water (brine) in pockets and in zones as continual supplies. At Weeks Island, an external shear zone, believed to be 600 feet thick in the salt itself, contains highly sheared and folded clay-size material and sand mixed with the salt.

Typically, unusual features within the salt stock appear to be located in or near mapped or suspected shear zones. These include natural-gas seeps, oil pockets, small gas-induced explosions, increased abundance of impurities, and a tendency for the salt to exfoliate. Often, the shear zones can be identified on the surface of the dome by topographic irregularities, such as platforms of various elevations and aligned valleys between the spines[55,56].

6.4 GEOMETRY OF THE WEST HACKHERRY DOME

The West Hackberry dome is one of the largest salt domes in the Texas-Louisiana onshore coastal region. It is part of a salt ridge that consists of the East and West Hackberry domes. In plan view, it is an elliptical piercement structure with its long axis oriented N73OE. The long axis of the dome is about 22,000 feet and the width is about 12,000 feet at the 9,000-foot contour (Figure 4.9).

Several interpretive maps have been constructed by various researchers to illustrate the geometry of the Hackberry salt stock. The first interpretation was compiled from relatively sparse data47. This map (Figure 6.9) contains details in places on the flanks of the West Hackberry dome; however, very little structure is shown over the dome because of the lack of subsurface control.

A map of salt geometry was prepared by the New Orleans Geological Society and is provided as Figure 6.10g3. This map was based on drill hole data that were available as of 1960. It is still used by many investigators to depict the geometry of the salt; however, considerably more data are now available to refine this map. In 1977, Norman Jenkins of Cities Service Company modified and partially updated the New Orleans Geological Society map as an exhibit for certification of caverns for Cities Services (Figure 6.11). Another map, Figure 6.12, was prepared by Jacobs/D'Appolonia, consultant to the Department of Energy for the West Hackberry SPR project. This map shows contours of top of salt within the general area of the site and represents a new interpretation: however, neither specific data points nor an explanation of how the map was derived are presented.

Figure 4.9 is a structure contour map of the top of salt that was prepared for this report utilizing available data from drill holes that have penetrated salt. The confidence level of this map varies, dependent upon the density of data. Where data are reasonably dense, the confidence level is plus or minus 50 feet; where data are sparse, the confidence level drops to plus or minus hundreds of feet.

The top of the salt over the West Hackberry dome is at an elevation of approximately -2,000 feet. Structure contours of top of salt have been drawn to -9,000 feet, although the dome (or the ridge extension of the dome) may extend to a depth of 30,000 feet to the source bed (Figure 4.9).

A major reentry exists along the minor axis of the ellipse that effectively divides the ellipse into two platforms. The east platform, which occupies much of Section 21 and parts of Sections 28, 22, and 16, drops off steeply to the north at an angle of about 77 degrees below elevation -2,500 feet, and at a gentler slope to the northeast and southeast at 53 degrees and 62 degrees, respectively. The west platform occupies parts of Sections 19, 20, 29, and 30. The north slope of this platform also drops off steeply, at an angle of about 72 degrees, while the west and south flanks drop off about 52 and 62 degrees, respectively.

In addition to the major north-trending reentry, there are several smaller reentries along the edges of the two platforms that correlate closely with faulting observed in the "B" sand (Figure 4.6).

6.5 RELATIONSHIP OF SALT STRUCTURE TO SALT GEOMETRY

The structure at the West Hackberry dome has been identified primarily by studying the geometry above and on top of the salt. Cores from selected intervals in four wells were studied, but no structural features were identified from the cores.

The overall geometry of the West Hackberry dome suggests that it is comprised of two spines, possibly more, separated by a boundary shear zone. The shear zone is interpreted as being located in the eastern parts of Sections 20 and 29, and corresponds to the major reentrant in the salt. Relief of the salt in and along the shear zone is quite variable. Closely spaced wells often show up to 50 feet of relief of the top of the salt. A comparison of the structure maps of the top of the salt (Figure 4.9), top of cap rock (Figure 4.7), and base of "B" sand (Figure 4.6) yields several interesting similarities. The postulated boundary shear zone, shown dramatically on the top of salt (Figure 4.9), is reflected on the structure map of the top of cap rock (Figure 4.7) and by faulting in the "Bll sand (Figure 4.6); and it may also be manifested in surface topographic features. The northeast-southwest trending faults identified on the "B*' sand base are reflected through changes in relief of the top of the salt and cap rock.

The internal structure of the dome (or spines) presumably is most complex near its center and along the junction of the spines and decreases in complexity away from those areas. The most complex zone of fracturing would be along the central boundary shear zone. The zone may contain a high percentage of impurities, possibly including hydrocarbons and sediment inclusions, and may also be a site of gas seeps. Faults and exfoliation areas might be encountered.

At the West Hackberry dome, as at other domes in Louisiana, there is an external shear zone that separates the interior salt mass from surrounding sediments. This zone at West Hackberry has been referenced in geologic reports as a gouge zone, or a zone of heaving shale. Where shear zones have been mapped in salt mines, they consist of an external shale sheath and internal salt sheath. The shale sheath zone is comprised of clay gouge that is often overpressured (heaving shale) and may grade outward to diapiric shale that has risen'with the salt. The shale sheath zone may extend hundreds of feet outward from the salt.

The salt sheath zone typically is characterized as an intensely sheared zone at the edge of the salt mass. Layering, when present, is sheared parallel to the outer boundary. The shear zone may extend hundreds of feet into the dome. No specific data are available on the salt sheath at West Hackberry dome; however, experience gained at other Gulf Coast domes suggests that a salt sheath probably accompanies the shale sheath near the periphery of the dome.

No major overhangs were identified during this study or previous investigations. Minor overhangs were interpreted by the New Orleans Geological Society to be present in Sections 19 and 16 (Figure 6.10)g3. Minor variations in the interpretation could readily eliminate any overhangs.

6.6 LITHOLOGY OF THE SALT MASS

Gulf Coast salt, in general, is noted for its high degree of purity; in fact, the Louann Salt is reported as the purest in the worlds4. The Louann Salt has been characterized by its lack of interbedded sediments (contemporaneously deposited sediments), its lack of soluble potash salts, and its relative lack of calcium sulphate (anhydrite and gypsum).

Kupfer suggests that the purification occurred during diapirism. He postulates that the relatively pure salt had more mobility than those layers or sections richer in impurities. The great distances involved in movement of regional Gulf Coast salt (8 to 15 miles) resulted in impurities being left behind as continuous recrystallization segregated the salts. Kupfer suggests that more impurities are probably present at depth, and that deep drill holes in coastal domes would encounter a higher percentage of other types of evaporites[54].

The lack of soluble potash salts may be further explained by the assumption that the brine from which salt was deposited was undersaturated with respect to potash. This assumption is consistent with the tectonic model of salt deposition. Few data are available on the petrologic composition of the West Hackberry dome. Core was obtained from four cavern wells for the West Hackberry SPR Site program (Woodward-Clyde Consult-ntsl**#123; and Appendix D, this report). Medium to coarsely crystalline halite and occasional anhydrite inclusions were described in three of the holes, while the fourth contained only medium to coarsely crystalline halite. During the current drilling and coring operations for expansion caverns, the recovery of transparent halite during one core run was reported (Whiting, personal communication). This would indicate a pegmatite-like zone of extremely coarse crystalline halite.

Most Gulf Coast salt domes are nearly pure halite with about 5 percent for fewer impurities. Approximately 3 percent of the salt core logged from West Hackberry dome was anhydrite. The sample was small but fits within the projected range. The density logs for wells SPR 101 and DOE 108 were reviewed to calculate percentage of anhydrite in the salt. For well SPR 101, approximately 3 percent anhydrite was calculated. This agrees with the estimate from the core logging. A short section (125 feet) from well DOE 108 was reviewed and approximately 8 percent anhydrite was calculated from this log; however, it is felt that this high percentage is not representative of the salt dome.

Three holes (20-6, 20-7, 20-8) drilled into the salt at West Hackberry dome were geophysically logged with a gamma-density tool. Mineralogy within the salt stock (other than halite) cannot be inferred from the logs due to the standard error of deviation of the tools. No other available geophysical logs were useful in lithology evaluation.

No reports of fluid or sediment inclusions in the salt were identified at the West Hackberry dome. Thus, no information is available on geochemistry or other hydrologic parameters of contained fluids. Studies of salt mines at other Louisiana domes have revealed inclusions of sediments, gas, brine, and petroleum within the salt mass56. The techniques used during the current drilling operations and the techniques proposed for leaching operations would not readily identify inclusions of materials or discontinuities within the salt.

6.7 UNRELIEVED STRESSES IN SALT

Surge caverns in salt domes along the Gulf Coast often experience pressure build-up when shut in. It has been reported that this same phenomenon is true with the existing caverns at the West Hackberry dome. Salt in these domes remains in a state of unrelieved stress. Cavern sides and floors are at a depth such that salt is in a semi-plastic state and will flow (creep) unless internal pressure is equal to or greater than overburden pressure.

A mechanical intrusion model for a typical dome has been postulateds4. In this model, the greatest unrelieved stresses within a dome or spine exist near its center, which is the area of new dome growth, greatest complexity of structure, and internal heat and stress. Boundary shear zones also exhibit high stress levels for these zones and delineate movement of one spine relative to another. By analogy, zones of greatest unrelieved stresses are expected near the central portion and the postulated boundary shear zone of the West Hackberry dome. However, data are currently insufficient to test this model at West Hackberry.

6.8 SALT DEVELOPMENT

Two companies have "mined" salt at the West Hackberry dome: Olin Corporation and Cities Service Company, Natural Gas Liquids Division. Olin's mining objective is the production of brine; Cities Service's leaching operation is to develop caverns in the salt for the storage of natural gas liquids.

6.8.1 Olin Caverns

-Olin Corporation and its predecessors have drilled 14 wells in the immediate vicinity of the West Hackberry SPR Site. These wells are designed for the specific purpose of leaching salt to produce raw feed stock for the Lake Charles soda ash plant. These 'wells, designated as 21-4 (Olin 1), 21-6 (Olin 2), 20-3 (Olin 3), 21-14 (Olin 4), 21-5 (Olin 5), DOE 6 (Olin 6) DOE 7 (Olin 7), DOE 8 (Olin 8), DOE 9 (Olin 9), 20-13 (Olin lo), DOE 11 (Olin ll), 20-6 (Olin 12), 20-7 (Olin 13), 20-8 (Olin 14), are shown on Figure 4.4 and Appendix A. The following discussion of early brining operations is extracted from a report to Olin Corporation'l.

The brine field was initiated in 1934 by drilling four brine wells (Olin 1 through 4) to produce raw feed stock for the Lake Charles soda ash plant. These wells were completed at an approximate depth of 2,650 feet. Initial plant capacity was 250 tons of soda ash per day but was doubled in 1941, increasing brine requirements from 225 to 450 gallons per minute ☎♑⬥✆. By 1944, the cavern developed in Olin 1 had coalesced with the cavern in Olin 2, and Olin 3 had coalesced with Olin 4 (Calley, Olin Corporation, personal communication) A fifth well, Olin 5, was drilled in 1946; however, little production history is available. Operating problems apparently forced its abandonment after 1948.

In preparation for a second plant expansion, Olin 6, 7, and 8 were drilled in 1946, and Olin 9 was drilled in 1947. These four'wells, which were completed at a depth of approximately 4,000 feet, increased brine output sufficiently to permit soda ash production of 1,000 tons per day in 1948.

By 1954, coalesced caverns Olin 1 and 2, and 3 and 4, had developed continuity with the cap rock and were abandoned. Olin 10 was commenced in 1957, but drilling problems were experienced. It was abandoned in 1958 prior to completion after a long, costly fishing job.

Cavern well DOE 11 was drilled in 1962. In 1973, the plant output of about 1,000 tons of soda ash per day was supported by production of approximately 900 gpm of 98 percent saturated brine from wells Olin 6, 7, 8, 9, and 11. This was accomplished by simultaneous production from any three wells while resting the remaining two.

Little data are available on the operation of the caverns between 1973 and 1977 when DOE acquired the 290-acre site containing the active brining caverns. Table 6.1 is a comparison of the volumes between the 1973 Fenix and Scisson estimates and the 1978 DOE measurements. The DOE volumes are based on the sonar caliper surveys run prior to certification in November 1977.

Caverns DOE 7, 8, and 9 were returned to Olin after certification for continued brining operations. Subsequently, Olin drilled Olin 12, 13, and 14 west of the DOE site (Figure 4.4). When brining operations for these new caverns were on-line, caverns DOE 7, 8, and 9 were returned to DOE's use.

<u>Location of Olin 2</u> - During the preparation of Figure 4.4, difficulties arose relative to the location of Olin 2 (21-6). The location on the completion report plotted Olin 2 just south of Olin 5 (21-5). Employees of Olin Corporation indicated that Olin 2 was located near Olin 1 (21-4). Figures 6.13 and 6.14, which are portions of maps on file with the Department of Conservation, Lake Charles, Louisiana, failed to clarify the problem. Figure 6.13 shows two wells in the southwest quarter of the northeast quarter of Section 21; one well has a total depth of 3,003 feet and the other a total depth of 2,655 feet. The well with a total depth of 2,655 feet fits the location and total depth of Olin 1. However, the location of the 3,003-foot well does not fit the location of Olin 2. The locations of Olin 1, 2, and 5 on Figure 6.14 do not fit any of the locations on the completion reports or the locations described by Olin; therefore, Figure 6.14 was not used for well location.

The location of Olin 2 (21-6) on Figure 4.4 is the location as described by Olin field personnel, who indicated the approximate location of the well heads (R. B. Calley, Olin

Corporation, personal communication). Although Olin personnel are confident of the locations of wells at the site, they may be in error in assigning numbers to the various wells; that is, Olin 1 may in fact be Olin 2. However, the matter of most concern is the location of the two wells.

6.8.2 Cities Service Company Product Storage

In 1957, Cities Service Company, Natural Gas Liquids Division began brining operations to form caverns for storing natural gas liquids (propane, N-butane, l-butane, ethylene, ethane propylene, and FG-butane). Three wells were completed that yeah followed by one in 1958, and one additional well in 1959. One additional cavern was added in 1967, three in 1969, and two in 1978.

As of March 1980, Cities Service had 11 caverns with an average capacity of about 1 million barrels each34. Cities Service has plans for adding five additional caverns, increasing their capacity to approximately 16 million barrels.

6.8.3 Abandoned Wells On-Site

Table 6.2 lists the basic data for the abandoned wells within the site boundaries. The locations of the wells are shown on Figure 4.4. The wells appear to have been drilled for either brine mining or sulfur exploration. Wells in the latter category were generally completed in the upper 100 feet of the cap rock and abandoned. They furnish little or no information regarding the salt dome, except the depth to and description of the cap rock.

Seven of the abandoned wells were drilled for brine production by Olin, including Olin 3 and 4, Olin 10, and Olin, Clara Ellender No. 2. Limited data regarding the Olin caverns are given in Fenix and Scisson[21]. Continuing studies have provided current information on existing storage caverns, but little data could be obtained about caverns 1 through 5. Olin had no records of the caverns, as they were commenced by a predecessor company. Discussions with field operating personnel provided the only available information.

Two abandoned wells were drilled near existing or proposed cavern wells. Clara Ellender No. 2 (20-l) lies near existing Cavern 6 and Union Sulfur, A.M. Barbe No. 1 (20-2) is near the location of expansion Cavern 101. Clara Elleder No. 2 apparently was plugged when abandoned. A.M. Barbe No. 1 has no plugging and abandonment record: however, this well reportedly only penetrated the cap rock.

6.8.4 SPR Expansion Caverns

Sixteen new caverns are planned (numbers 101 through 116 on Figure 4.4). The drilling, sampling, and leaching programs for the expansion caverns are described in other reports[96,97]. The caverns will be leached by the reverse circulation method. The initial leach plans call for caverns of 11 million barrels storage capacity with an additional one-million barrel sump to accomodate the expected 5 percent of non-soluable materials in the salt and another one-million barrel excess capacity to compensate for salt creep for brine buffer zone and as a safety factor in predetermination of the lowest oil/brine interface depth. A final storage of 20 million barrels is anticipated after five recyclings of the cavern. The desired (planned) characteristics for all of the expansion caverns are listed below:

Cavern Shape:	"Flower Pot"
Top of Cavern:	-2,700 feet
Cavern Height:	2,000 feet

Cavern Spacing:	750	feet
Cavern Diameter:	270	feet (after five cycles)
Pillar Width:	480	feet
P/D Ratio:	1.78	

The maximum depth limit is controlled by economics and the creep behavior of salt. For the present program, the maximum desired depth for base of the cavern is approximately 5,000 feet (Whiting, personal communication). The logging and coring programs associated with the expansion caverns are more extensive than those for the original caverns. Additional information regarding the internal consistency of the salt, cap rock, and overlying sediments is expected to become available as this program develops.

6.8.5 Existing Caverns

The SPR Program's storage facilities at West Hackberry currently consist of five caverns, DOE 6, DOE 7, DOE 8, DOE 9, and DOE 11, providing approximately 52 million barrels of gross storage volume. The most complete set of data on the individual caverns is presented in the volumes of Certification and Useability24~25~26~27~28. Further data on Cavern 6 may be found in Whelply'*l.

The principal facts regarding each of the five existing caverns are summarized in Table 6.1. The locations of the surface wells are shown on Figure 4.4. The basic cavern shapes and their spatial relationships are illustrated in Figures 6.15 through 6.19. The shapes are derived from sonar caliper surveys conducted in 1977 during certification procedures. Some changes may have occurred in cavern shape and size since that time. Specifically, caverns DOE 7, DOE 8, and DOE 9 were returned to Olin for continued brining operations after certification. Cavern DOE 6 was the scene of a fire in

November 1978 and is currently (May 1980) undergoing recertification tests. New sonar caliper logs will be run as part of the recertification. Technical data on the sonar caliper technique of cavern surveying are provided in Dawson-Grove and Dow Chemical 13t16.

Critical criteria for cavern dimensions, shapes, and locations have been established for the SPR storage caverns. These criteria are briefly discussed in each of the certification volumes24~25~26~27~28 and include:

- Minimum distance between edge of cavern and edge of salt dome: 300 feet.

- Minimum distance if edge of salt dome is not well defined: 500 feet.

- Minimum separation of cavern sidewells for caverns storing different materials: 200 feet.

Based on the certification data, the following recommendations were made at the time of certification:

1) Further tests should be to map the edge of the salt dome nearest cavern DOE 6 to establish the distance between the edge of the dome and the cavern. These tests should be done prior to recycling the cavern. (Seismic and gravity surveys conducted in May 1980 may assist in providing these answers).

2) Because of the high diameter/roof ratio of 5.3/l, cavern DOE 6 should not be operated at roof pressure less than a static column of brine until further tests prove it is safe to do otherwise.

3) Caverns 8 and 9 have a minimum 160-foot separation. These caverns are expected to coalesce after three fresh-water displacement cycles. Coalesence of the caverns is not considered a failure but would lead to a mixing of the stored products. Certification of caverns 8 and 9 was based on storage of compatible crude oils.

Cavern shape is a reflection of a number of factors, including the basic leaching process, specific controls enacted during leaching, the location of insoluble zones within the domes, and the nature of internal structures of the dome. The cavern shapes at West Hackberry may reflect some internal properties of the dome: however, there is insufficient information regarding the leaching process of the caverns to draw any conclusions.

TABLE 6.1

WEST HACKBERRY CAVERN DEVELOPMENT

1973 - 1977

CAVERN NO.	CAVERN VOLUMESa 1973	1975	1977
6	4.8b	14.6'	12.2
7	ll.Ob	14.1c	12.3
8	12.gb	20.4'	10.1
9	7.9	--	8.9
11	6.8	--	8.5

a All volumes are in millions of barrels and are based on sonar caliper measurements unless otherwise indicated.

b Estimated by Fenix and Scisson (1973).

c Sonar caliper measurements in 1975 appeared to produce erroneous results. A possible explanation is provided in Gulf Interstate Engineering Company, (1977a, b, c).

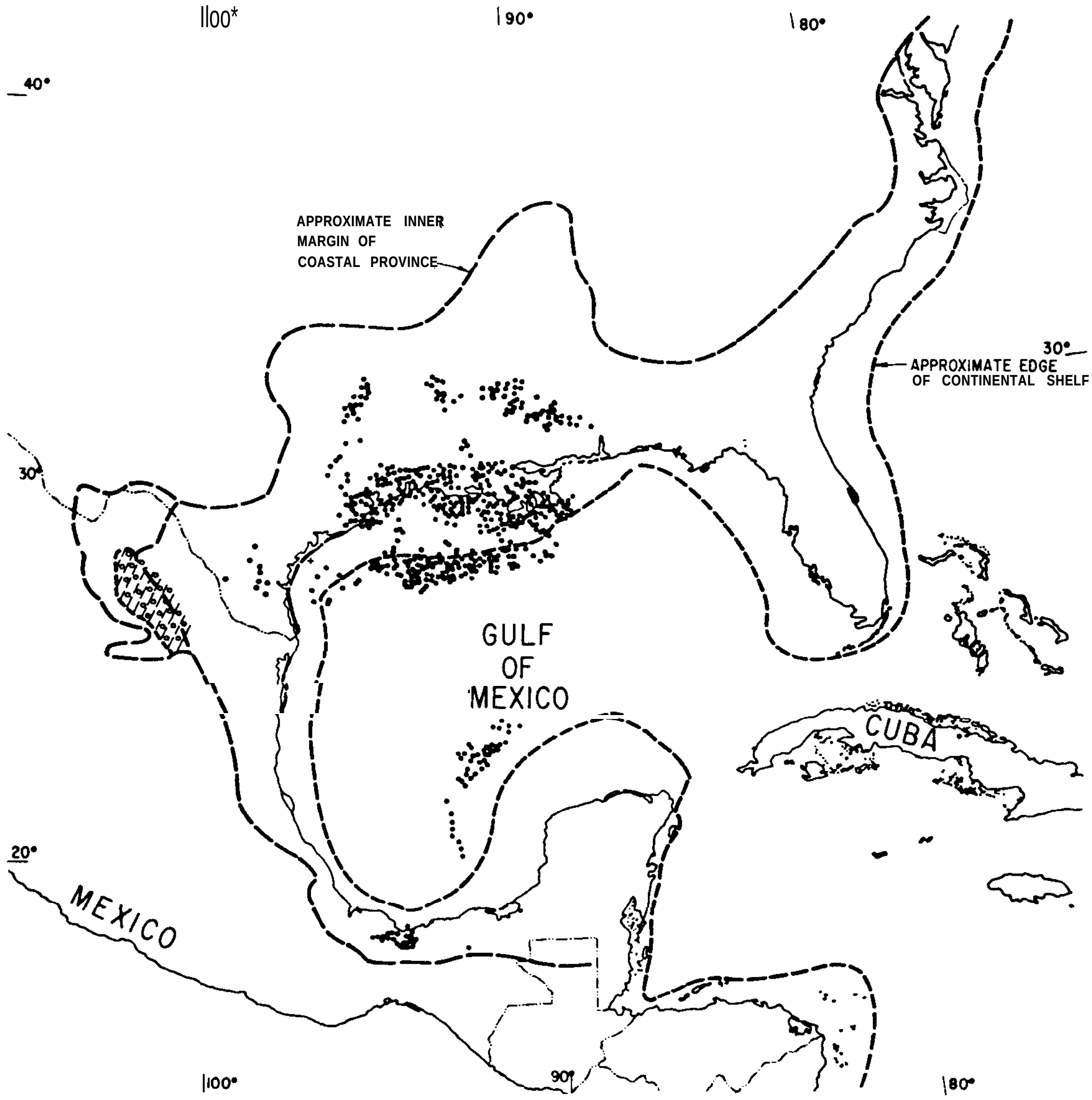
TABLE 6.2

ABANDONED WELLS IN THE VICINITY OF THE
WEST HACKBERRY SPR SITE

BASE MAP NO.	OPERATOR & LEASE NAME	DATE ABANDONED	PLUGGING INTERNAL (MET)	TOTAL DEPTH (FEET)	COMMENTS
20-l	Olin Clara Ellender #2	January 1948	11-45, 350-450	2152	Proposed Brine Well (?)
20-2	Union Sulfur Co. A. M. Barbe Xl	January 1927	Not Plugged	1645	Sulfur Exploration
20-3	Olin $3* J. C. Ellender Xl	April 1954	O-50, 1050-1200	1900	Brine Production
20-4	Pan Am Agnes Lowry tl	December 1968	25-50, 1440-1450	1595	Sulfur Exploration
20-10	Freeport Sulfur Hanzen #I	3une 1944	512-612, 1601-1701	1775	Sulfur Exploration
20-13	Olin C. N. Ellender #7	July 1958	O-10, 1050-1250	1525	Brine Development
20-14	Olin 14 C. N. Ellender #l	March 1954	O-SO, 1105-1205	1850	Brine Production
20-15	Union Sulfur Co. J. C. Ellender #l	January 1927	-a-	1680	Sulfur Exploration
20-16	Union Sulfur Co. J. C. Ellender X2	---	---	---	Sulfur Exploration
20-19	Union Sulfur Co. Clara Ellender #l	January 1927(?)	Not Plugged	1639	Sulfur Exploration
21-1	Carrl Oil E+Al J. C. Ellender Xl	December 1954	-we	1554	Sulfur Exploration
21-13	Freeport Sulfur C. N. Ellender Xl	June I944	1551-1585	1645	Sulfur Exploration

(Locations Plotted on Figure 4.4)

***Note**: This well is not within the confines of the site; however, the caverns of Olin #3 and #4 have coalesced and, therefore, Olin #3 is included in this table.

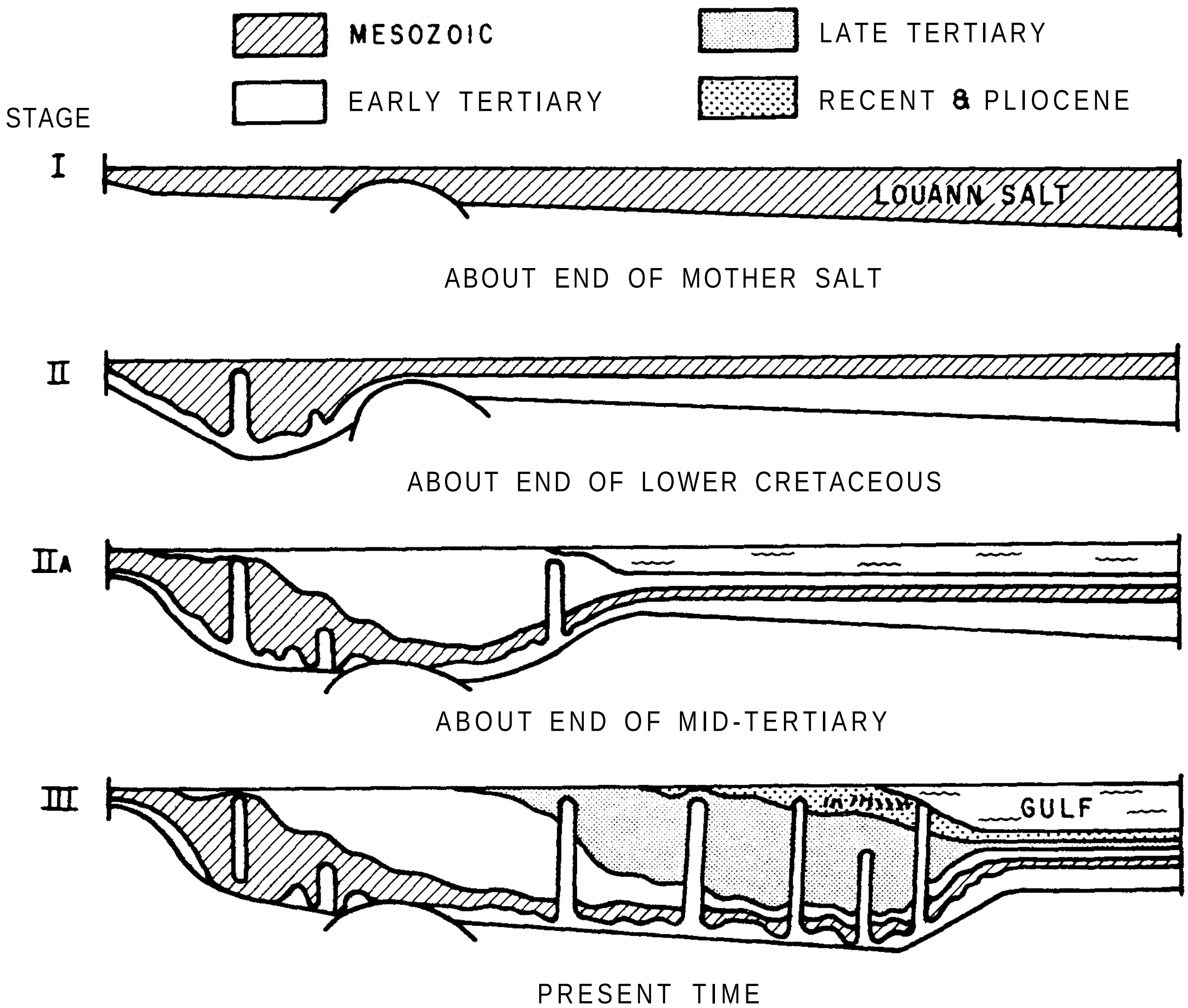


Source: Murray, 1961

EXPLANATION

- • Salt dome or probable salt dome
- + Shale dome
- Area of thick jurassic gypsum and gypsum (?) domes

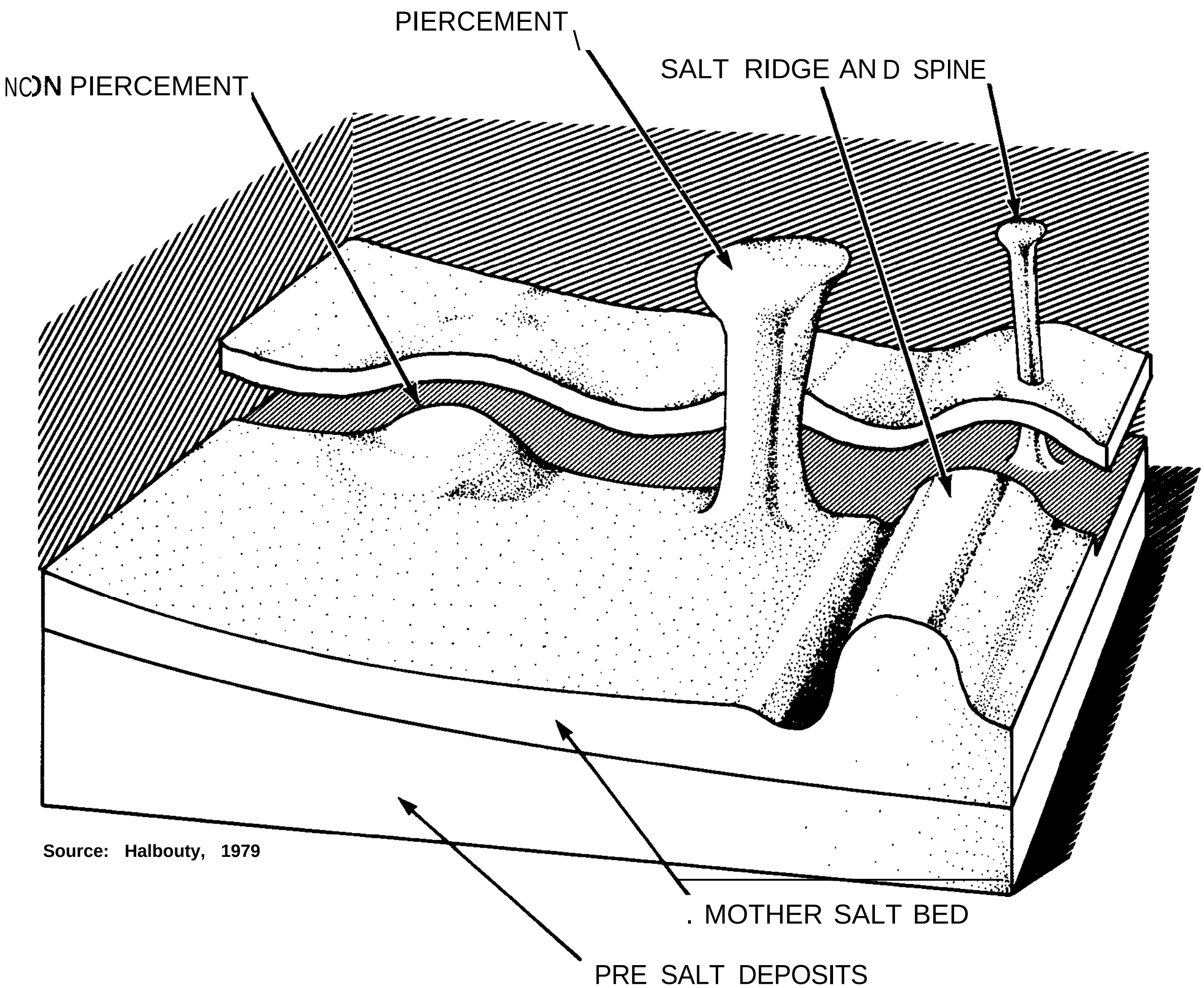
Figure 6.1
DISTRIBUTION OF SALT DOMES IN THE GULF REGION



Source: Hanna, 1959, in Andrews, 1960

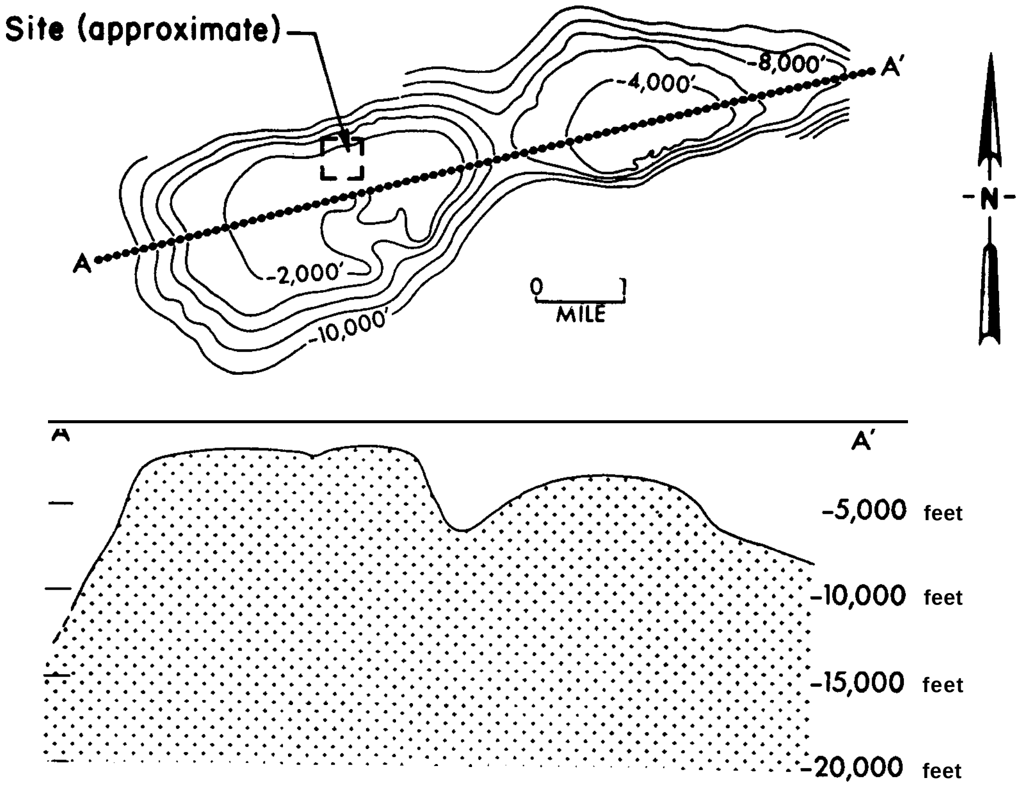
Figure 6.2

STRUCTURAL EVOLUTION OF INTERIOR AND COASTAL SALT DOME BASINS OF GULF REGION



Source: Halbouty, 1979

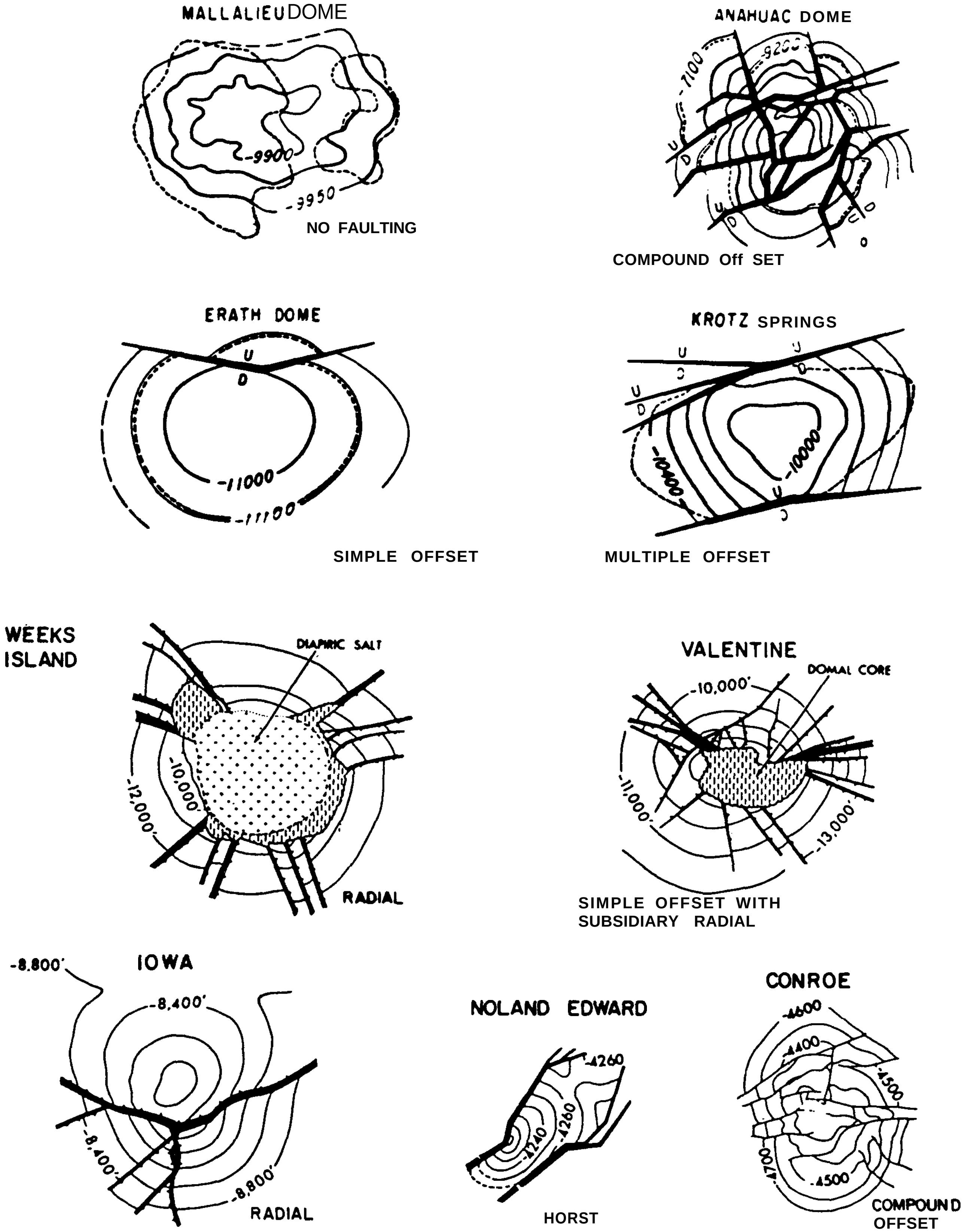
Figure 6.3
SCHEMATIC OF PIERCEMENT AND
AND NON-PIERCEMENT DOMES



Source: New Orleans Geological Society, 1962; Murray, 1966

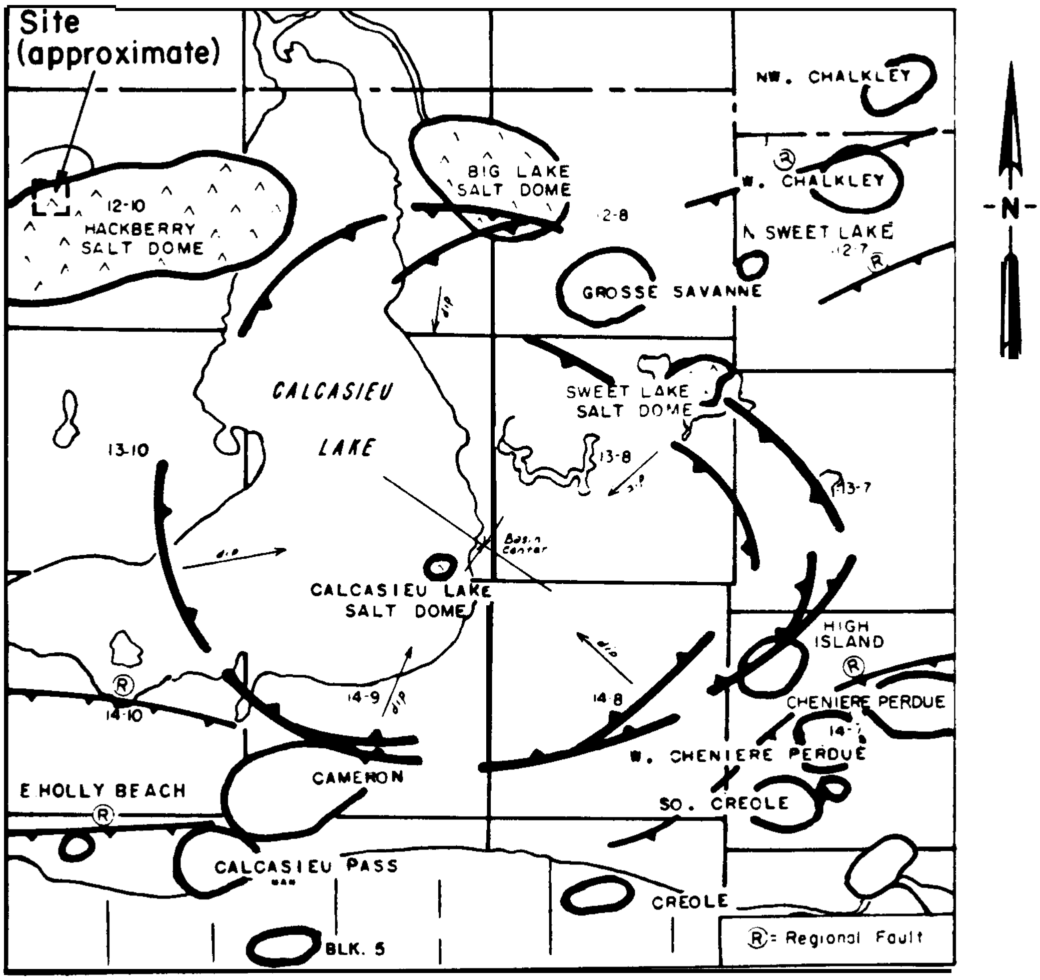
Figure 6.4

SALT RIDGE CONTAINING EAST AND WEST HACKBERRY DOMES, CAMERON PARISH, LOUISIANA



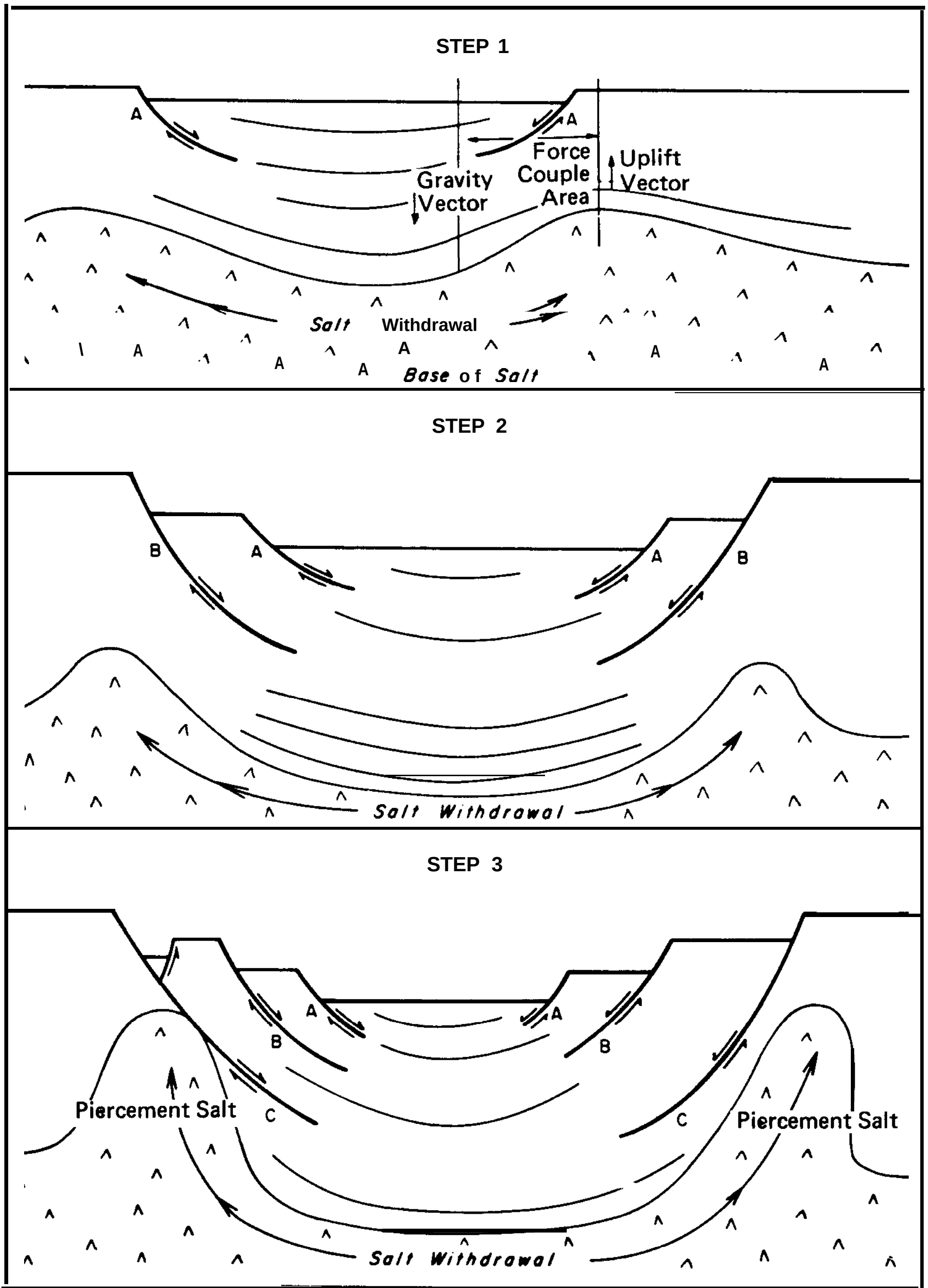
Source: Atwater and Foreman, 1959; Carlos, 1953; Murray, 1961

Figure 6.5
STRUCTURAL CONTOUR MAPS OF PRINCIPAL TYPES OF OFFSET FAULT PATTERNS



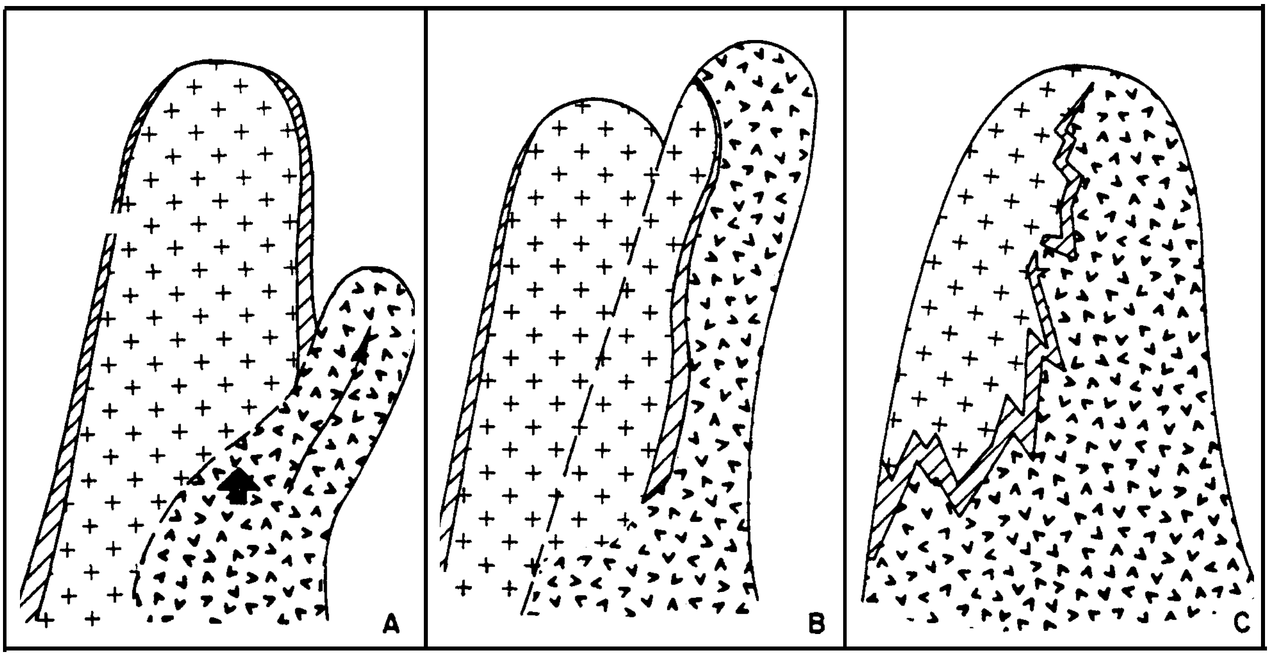
Source: Seglund, 1974

Figure 6.6
CALCASIEU LAKE COLLAPSE-
FAULT SYSTEM



Source: Seglund, 1974

Figure 6.7
FORMATION OF COLLAPSE-FAULT SYSTEM OVER SALT-WITHDRAWAL BASIN



Source: Kupfer, 1974b

A. New spine of salt being activated by heat and buoyancy will exert pressure on the soft and mobile salt at point of arrow.

B. This is the more probable type of movement that will take place under the conditions at 'A', resulting in a boundary shear zone. Dashed line is also a shear zone (internal type).

C. Shale sheath of 'B' has been folded by a second remobilization (flowage) resulting in a folded boundary shear zone.

Figure 6.8

POSTULATED SALT DEFORMATION PROCESSES

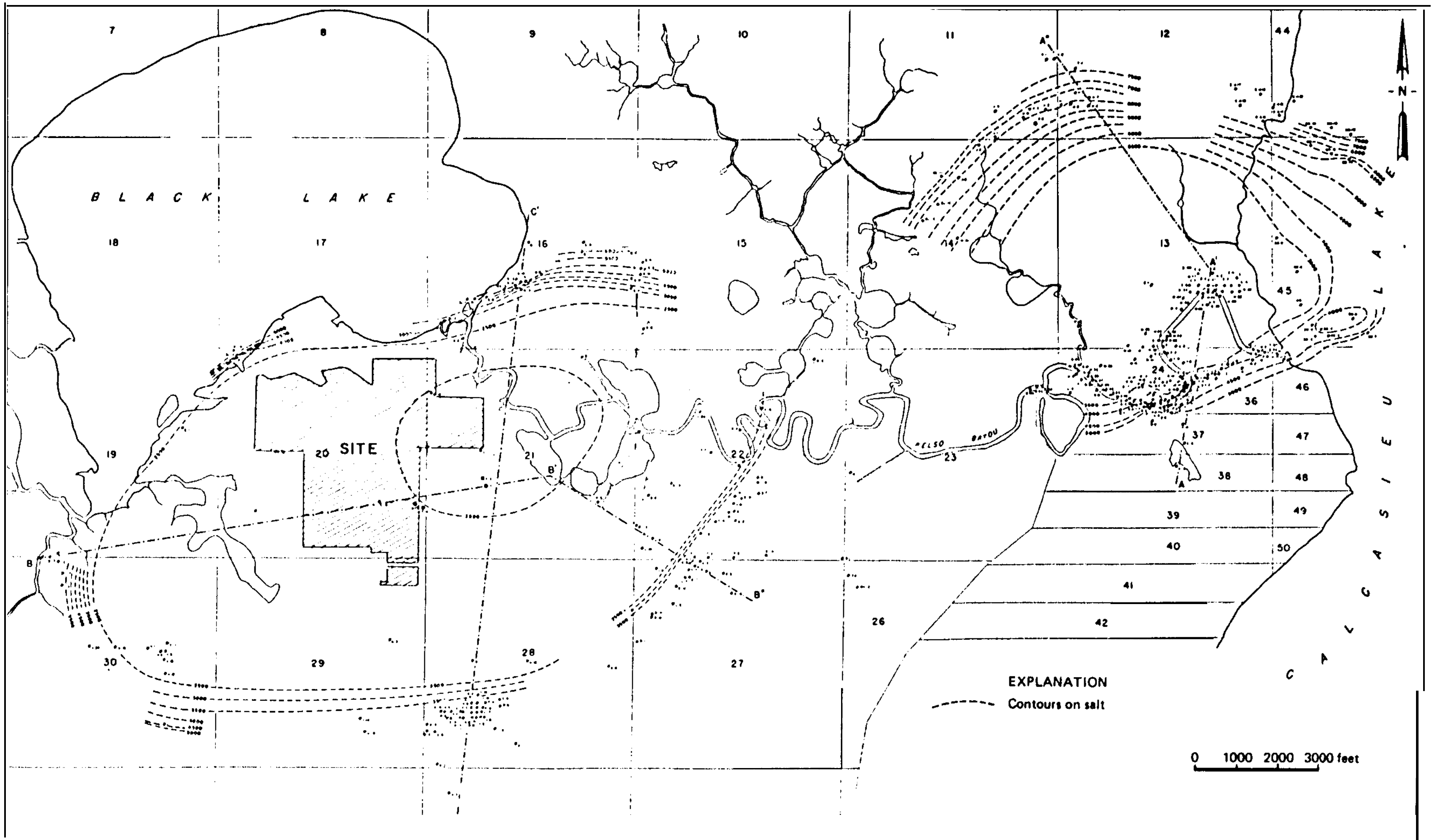


Figure 6.9
HOWE AND OTHERS (1935) STRUCTURE CONTOUR MAP OF TOP OF SALT

SANDIA – Project No. 14620A

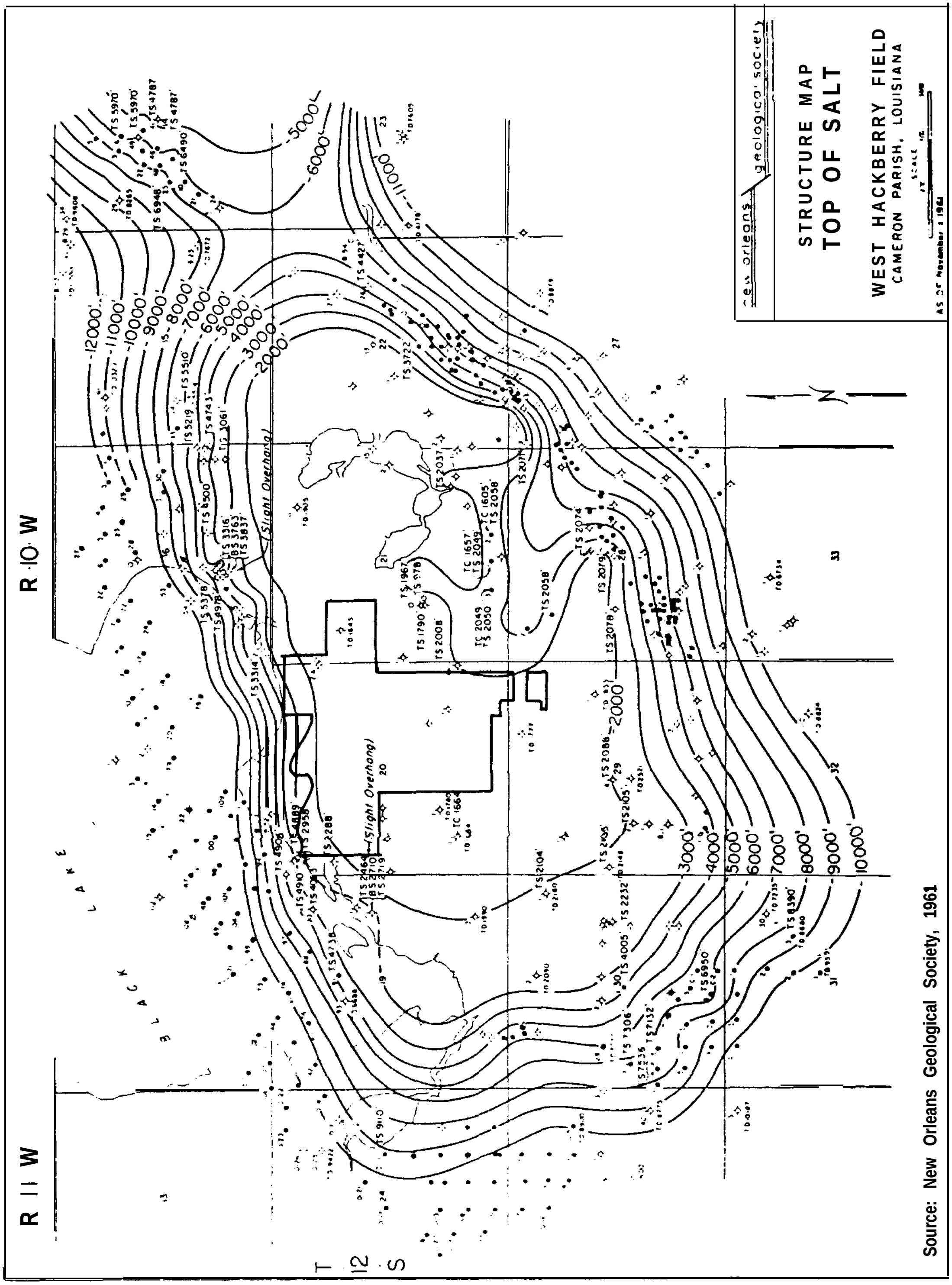


Figure 6.10

NEW ORLEANS GEOLOGICAL SOCIETY (1961) STRUCTURE CONTOUR MAP OF TOP OF SALT

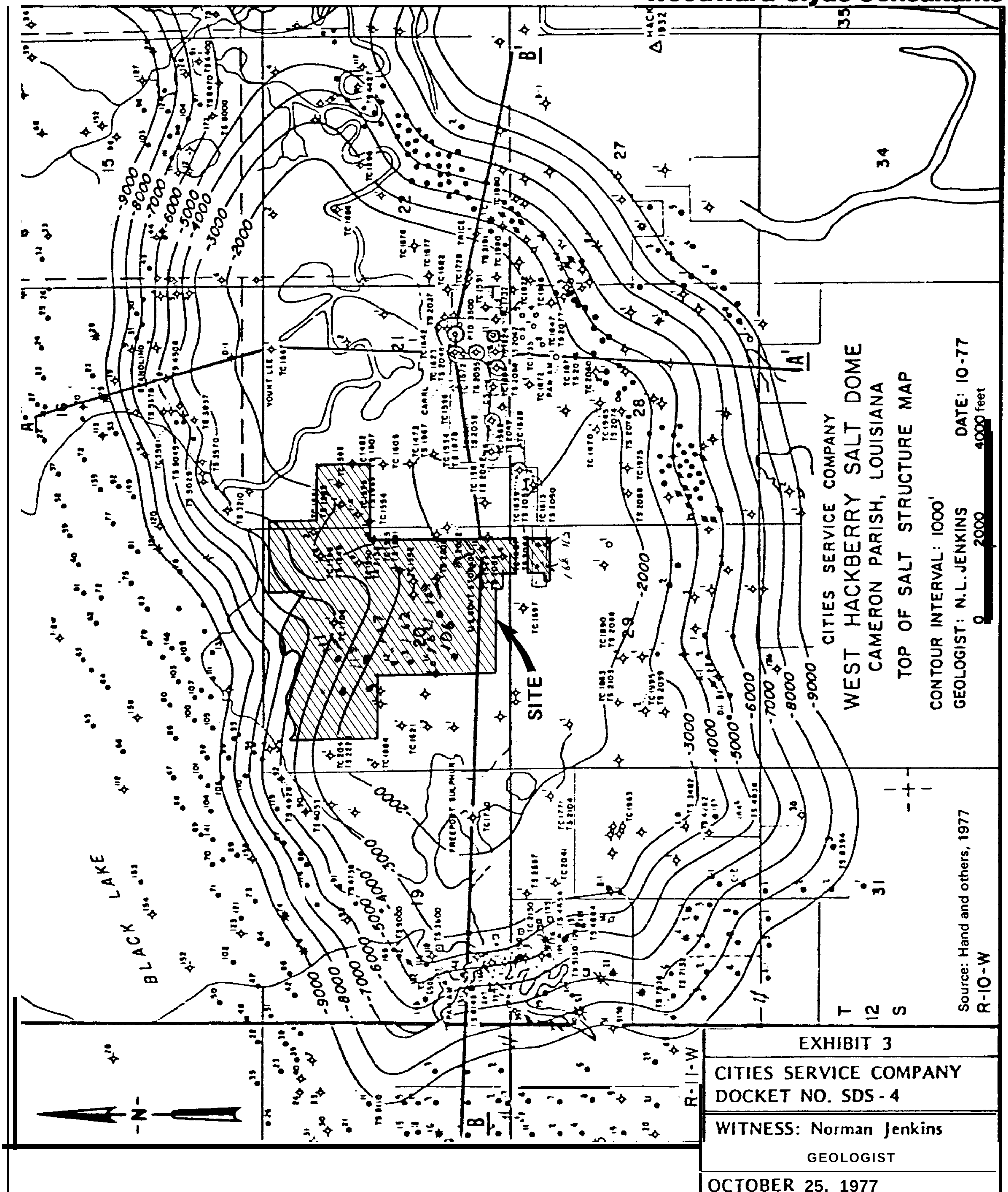
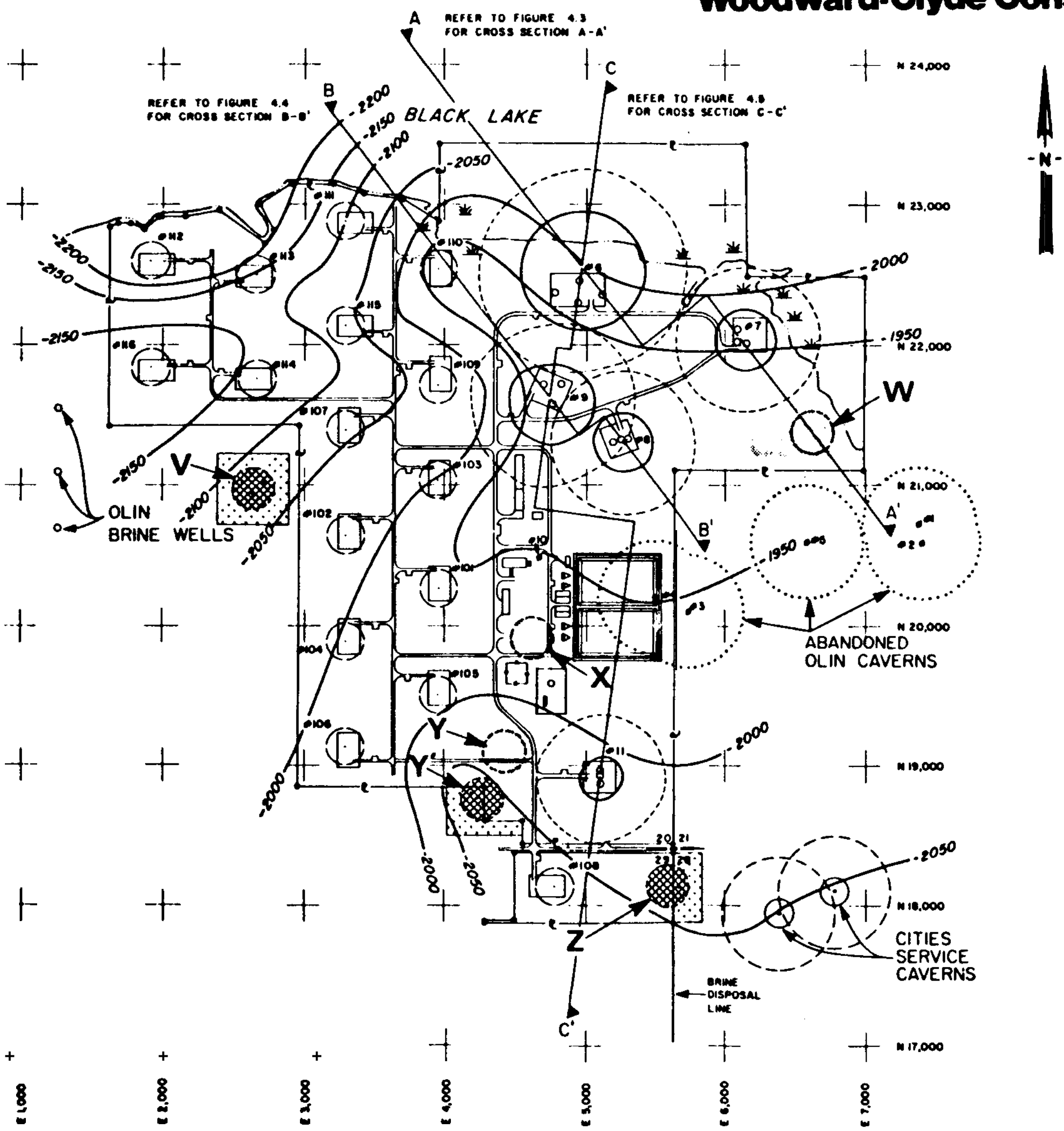


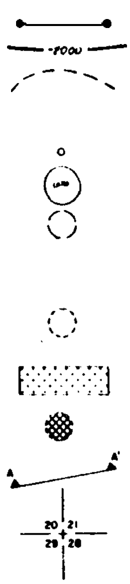
Figure 6.11

CITIES SERVICE (1977) STRUCTURE CONTOUR MAP OF TOP OF SALT



Source: Jacobs / D' Appolonia

EXPLANATION



- Property line
- Salt contour (depth in feet)
- Limit of 300 foot pillar around deep caverns only
- Surface well location (proposed)
- Surface well location (existing)
- Maximum cavern diameter (existing)
- Maximum cavern diameter (proposed 20 mmb maximum cavern volume)
- Areas evaluated for surge cavern location
- Optimum location within evaluated area - surge cavern
- Additional land acquistion necessary to site surge cavern
- Surge cavern locations subject to additional land acquistion
- Cross-section line
- Section corner

NOTES:

1 Locations for Olin caverns and wells are approximate

Salt contours are approximate and based on borehole data and projected points

Cavern shapes show maximum radius at 45° intervals at any depth

Grid is based on site specific coordinates

0 400 800 1200 feet

Figure 6.12
JACOBS/D'APPOLONIA (1979) STRUCTURE CONTOUR MAP OF TOP OF SALT

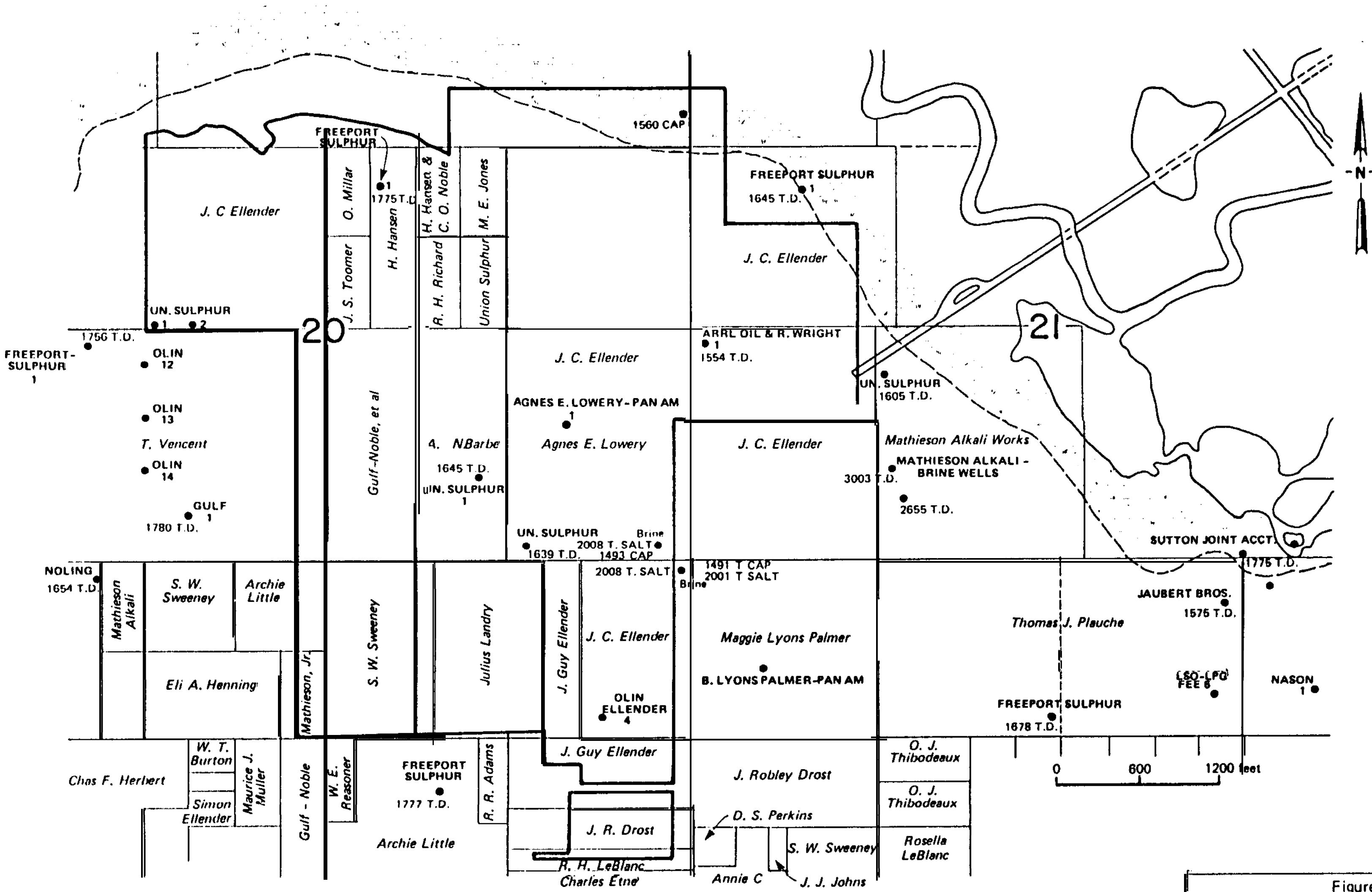


Figure 6.13
PORTION OF WELL LOCATION MAP ON FILE WITH THE DEPARTMENT OF CONSERVATION, LAKE CHARLES, LOUISIANA

SANDIA – Project No. 14620A

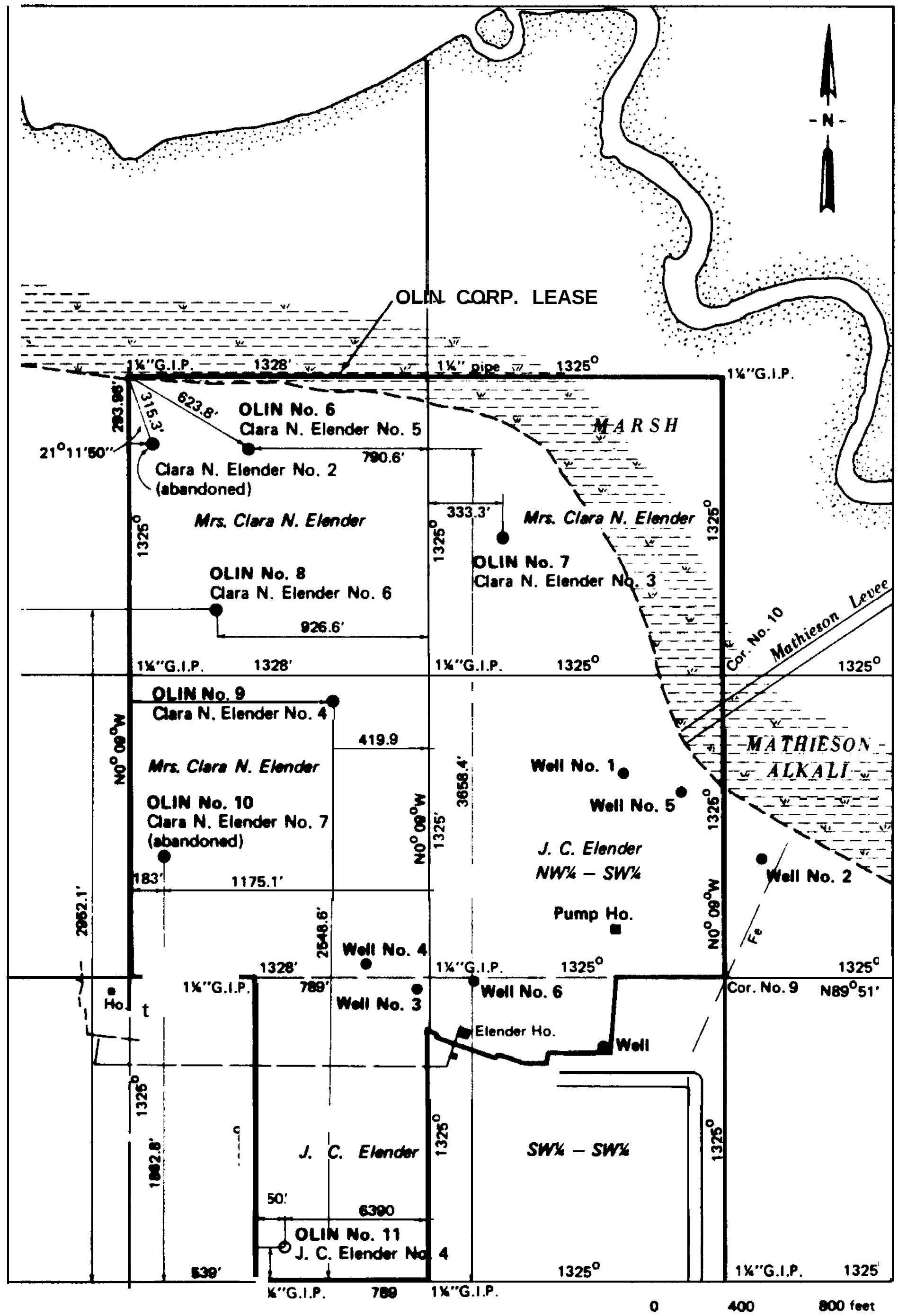


Figure 6.14

MAP FROM OLIN FILE AT THE DEPARTMENT OF CONSERVATION, LAKE CHARLES, LOUISIANA

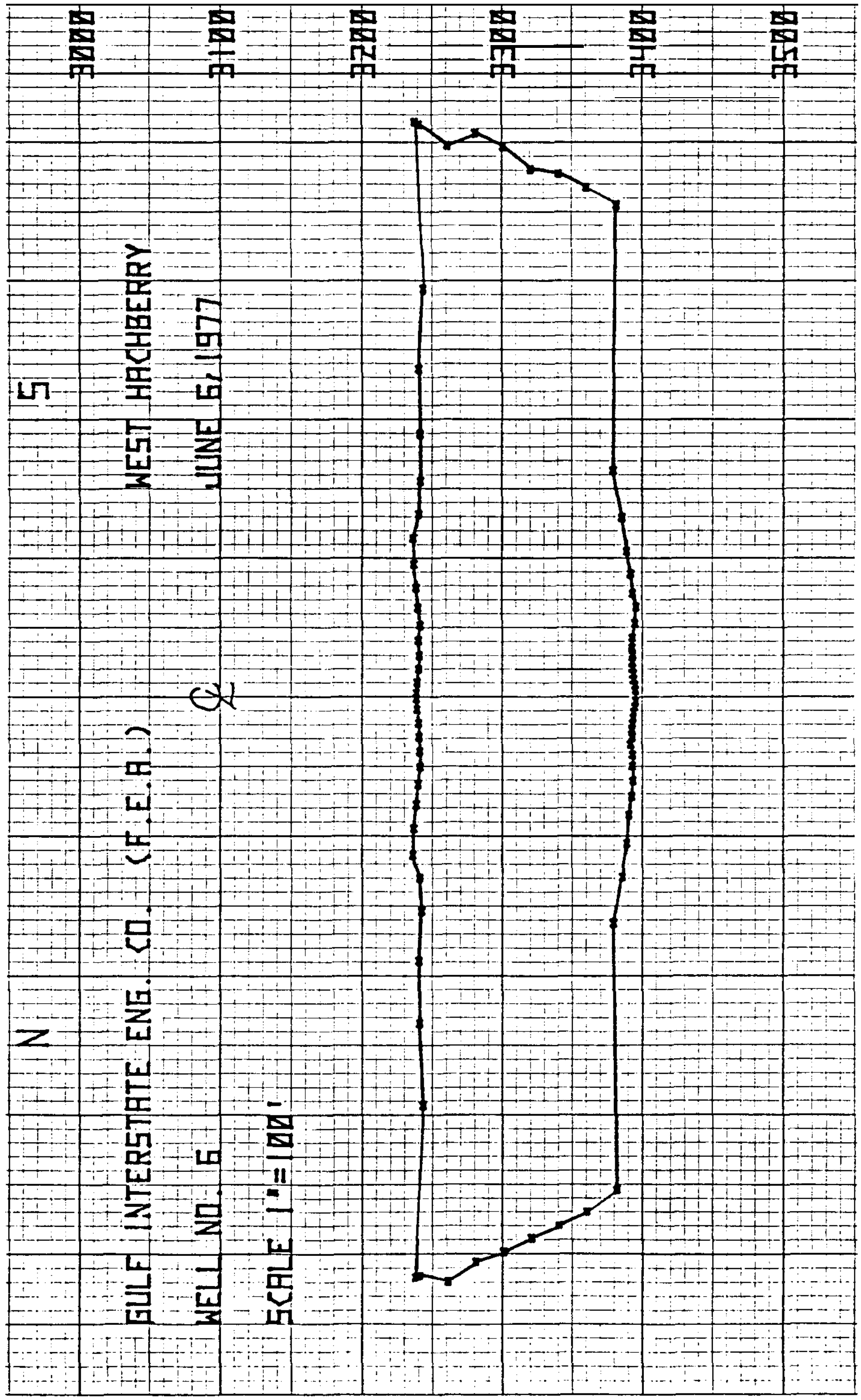


Figure 6.15
SONAR CALIPER SURVEY LOG
DOE 6

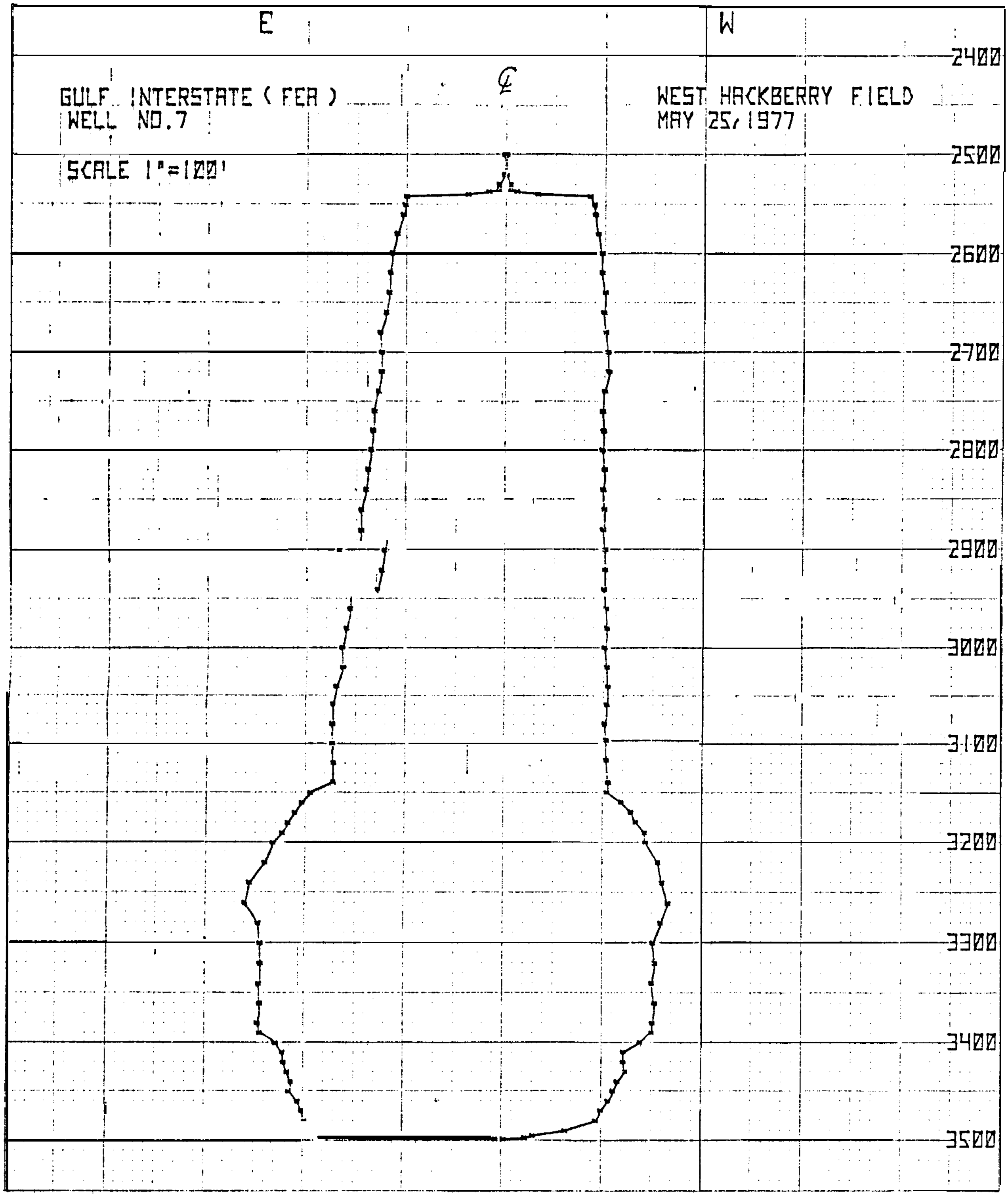


Figure 6.16
SONAR CALIPER SURVEY LOG
DOE 7

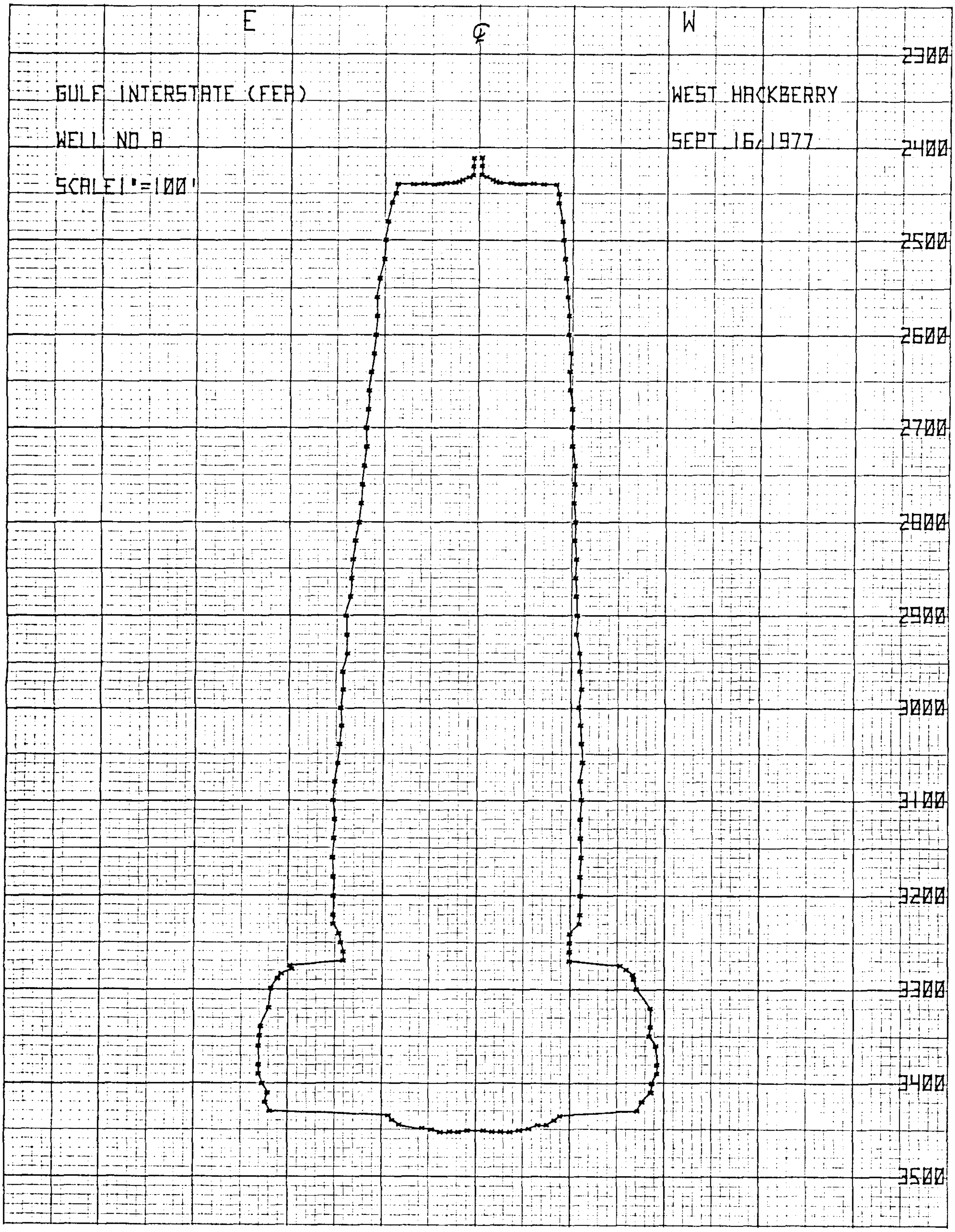


Figure 6.17
SONAR CALIPER SURVEY LOG
DOE 8

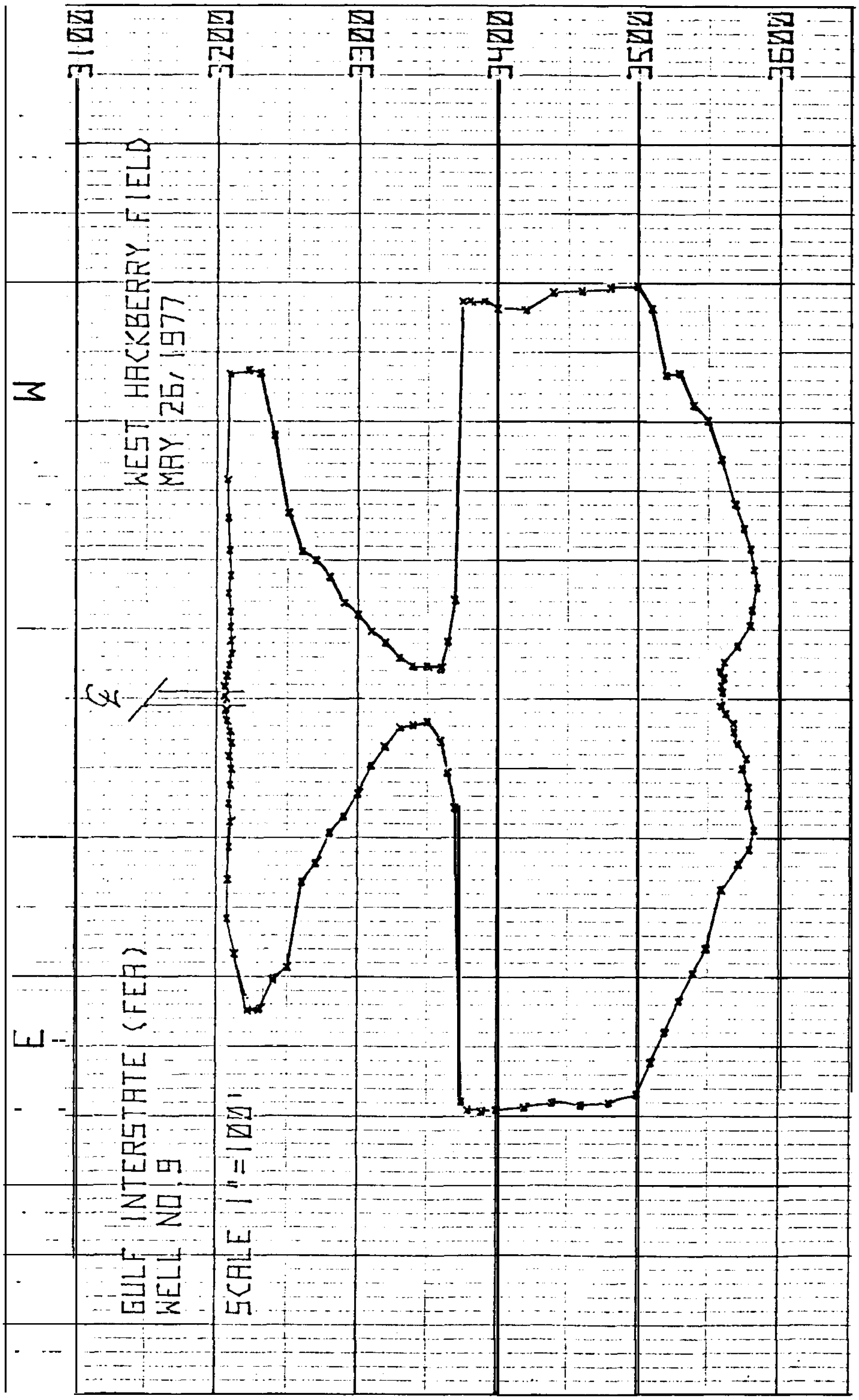


Figure 6.18
SONAR CALIPER SURVEY LOG
DOE 9

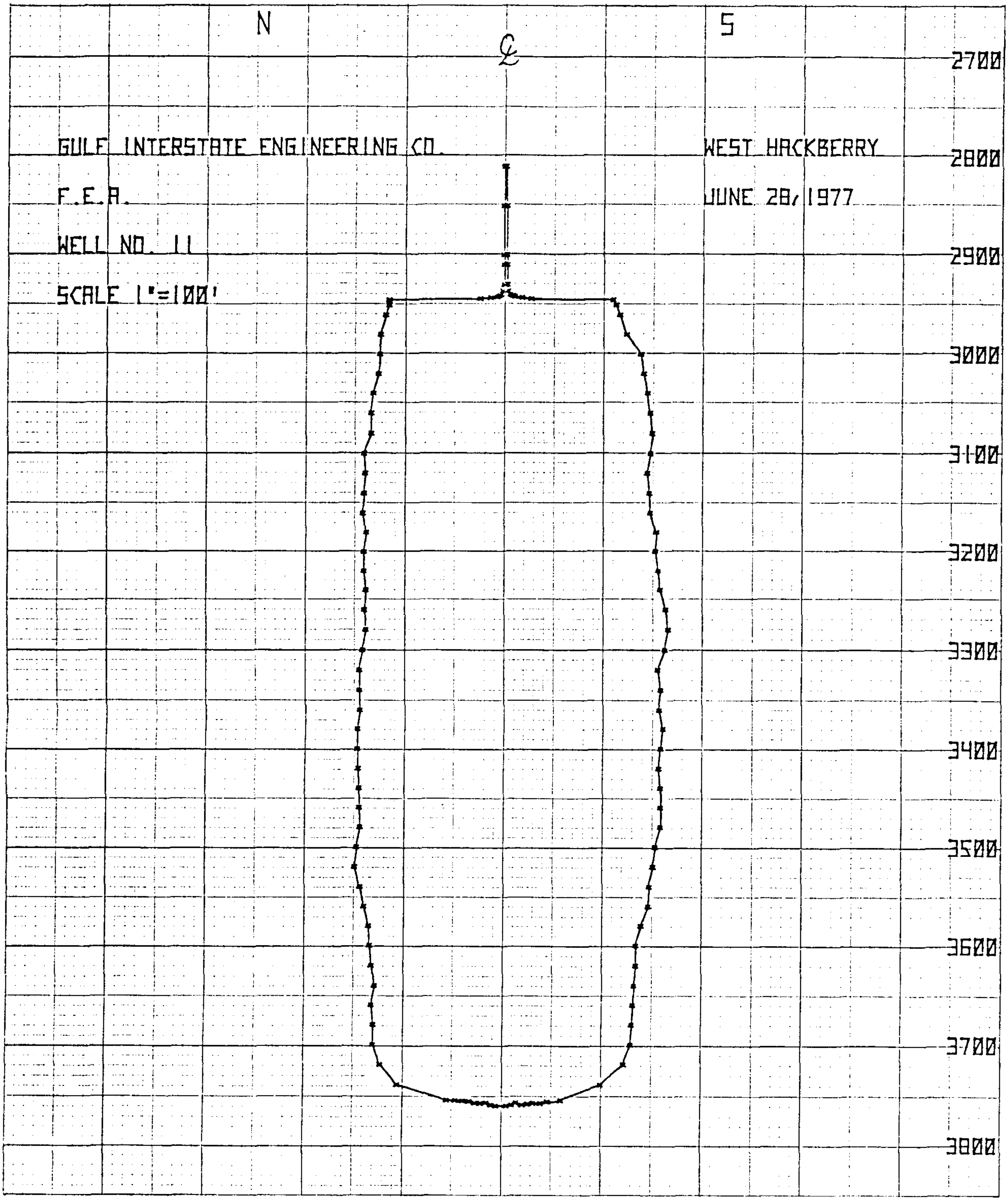


Figure 6.19
SONAR CALIPER SURVEY LOG
DOE 11

7.0 HAZARDS, MITIGATING MEASURES, AND LONG TERM MONITORING

A hazard, as used in this report, is a geological, hydrological, or meteorological condition that represents a risk or concern to: 1) the design, operation, or abandonment of the SPR facilities; 2) the safety of personnel at the site or in the surrounding area; or 3) the environment as a result of SPR facility operations. Three types of hazards are potentially present at the West Hackberry SPR Site: 1) natural hazards; 2) design, construction, and operations hazards; and 3) man-induced hazards.

It has been suggested that "containerless storage facilities" (i.e., salt caverns) "must" meet three important requirements: impermeability, stability, and economylg. Economic considerations are not part of the scope of this discussion. Impermeablility of salt and stability of caverns are critical considerations to storage and recovery of petroleum at the site. These and other geologic conditions are discussed below.

7.1 NATURAL HAZARDS

Natural hazards are processes over which man has no control. In most cases, it is possible to assess whether or not a natural hazard exists at a site. In some cases, it is possible to predict the magnitude and probability of occurrence during the lifetime of a project. The natural hazards that could affect the site are discussed below.

7.1.1 Earthquakes

The historical seismicity and seismic potential of the Gulf Coast region is discussed in Section 3.5 of this report. The area is characterized by a low level of historical seismicity, and the few earthquakes that have occurred were of low magnitudes. In addition, the level of tectonic activity is low, and the capability of the Gulf Coast sediments to accumulate significant tectonic strain is small. Although earthquakes may occur in the region during the lifetime of the facility, it is not expected that any significant damage would result at the site from either seismic shaking or potential tectonic surface fault rupture.

7.1.2 Natural Subsidence

Natural subsidence refers to differential movement of the ground surface above the dome relative to adjacent areas due to continued uplift of the salt dome or compaction of the surrounding sediments. The magnitude of this process is probably no more than a few inches per 100 years; therefore, natural subsidence is not considered to present a significant hazard to the facility. Other types of subsidence are discussed in Section 7.3.2.

7.1.3 Hurricane-Induced Flooding

Estimates of the storm-surge level of the loo-year hurrricane in the West Hackberry area are from 4.5 and 6.5 feet above mean sea level. As discussed in Section 4.7.5, these estimates are based on storm-surge models that may not represent state-of-the-art estimates. A Corps of Engineers study in the Lake Sabine area (30 miles west of the site) would project a 10.5-foot-high surge as far inland as West Hackberry.

The elevation of most of the West Hackberry site is above a potential lo-foot-high surge. Therefore, hurricane-induced flooding is not expected to have a significant impact on the long-term operation of the facility. There could, however, be significant interruptions in the day-to-day operation and maintenance of the facility as a result of flooding and wind damage associated with hurricanes. Access to the site would be severely limited due to flooding of adjacent low-lying areas.

7.1.4 Non-Tectonic Fault Displacement

The faults in the vicinity of the West Hackberry dome are non-tectonic and are related to the emplacement of the salt. These faults have displaced Quaternary sediments (Section 4.4.2), and renewed displacement on some of these faults may occur within the lifetime of the SPR project. Any surface facilities that are situated on top of a fault or any well that crosses a fault in the subsurface could be damaged.

7.2 DESIGN, CONSTRUCTION, AND OPERATION HAZARDS

The hazards included in this category are those geologic and/or hydrologic conditions that can create problems in the construction or operation of the facility but that in general can be corrected or controlled. These conditions should be identified and considered in the planning and design of the facility. The geologic conditions discussed below either are known to be present at the West Hackberry SPR Site or have been encountered in other salt domes and potentially could be present at the site.

7.2.1 Geologic Conditions Associated with Sediments

The geologic conditions and/or processes associated with the sediments overlying the dome can affect the stability of surface structures and drilling and completion operations. The surface Holocene soils at the West Hackberry dome are comprised of beds of clayey to sandy silts. These soils are eolian in origin; individual elastic grains have a preferred orientation that has maximized the porosity of the soil mass. Cementation is present only on limited grain contact surfaces. These soils are subject to rapid collapse upon loading and wetting, so differential settlement of structures may be a sensitive design concern (see Section 4.5). Proper investigation, planning, and engineering design can address the problem of collapsible soils with minimum risk to facilities.

Gravelly sand units are present in the Pleistocene sediments over the dome. These units locally have a high porosity: thus, there is a concern for circulation loss in drilling these zones. Lost circulation may result in blowouts or hole collapse.

Highly plastic shale or clay beds are present in the sediments overlying the dome. The plastic beds are known to expand and block uncased holes, which may result in the binding of drill bits or closure of the hole above the drill bit. In both instances, drilling fluid circulation is inhibited or lost, and hole advancement may be impeded.

7.2.2 Geologic Conditions Associated with Cap Rock

The geologic conditions and/or processes of the cap rock may affect both drilling and leaching operations and long-term integrity of elements of the West Hackberry SPR facility. Cap rock throughout the Gulf Coast region is noted for problems related to circulation loss during drilling operations. Several occurrences of such problems were noted at West Hackberry: reentry well DOE 6A encountered an 8-foot cavity in cap rock during drilling[72], the Olin 10 drill hole was abandoned due to problems with sticking tools while drilling in the cap rock" circirculation problems have been encountered in some expansion wells currently being drilled (G. Whiting, personal communication).

High permeability and porosity and resultant cirulation problems while drilling may result in problems that include:

- Circulation loss in gas zones may lead to well blowouts.

- Bits, drill stems, and other drilling equipment, as well as the test hole itself, may be damaged when drill strings drop, as in a cavity.

- Drill strings may become stuck through lost circulation, resulting in a minimum of lost time and perhaps as much as a lost hole.

- Cement bonds may be incomplete owing to lost circulation, which can lead to leakage in or out of casing strings, corrosion, and decreased support for casing strings, etc.

Most of the above problems can be overcome by anticipating the problems in the design, and by good construction practices.

Wherever cavernous conditions are present in the cap rock, there is a risk to stability and integrity of the cavern in the salt. Block movements may also occur along deformational zones in the cap rock induced by salt movement. This may represent a risk to the long-term integrity of casing in cap rock, as the casing may be sheared due to mass rock movement.

7.2.3 Shear Zones

In addition to the potential for differential displacement across faults (discussed in Section 7.1.4), other problems associated with shear zones could affect the construction and operation of the facility. The types of shear zones generally associated with salt dome emplacement are discussed in Section 6 and the principal zones interpreted to exist at the West Hackberry SPR Site are described in Sections 4.4.2, 5.2, and 6.3.

One of the most significant problems commonly associated with shear zones is high porosity and permeability of the rock mass within the zone. Locally interconnected cavities may also exist in shear zones. These problems could result in significant leakage of stored petroleum products and may eventually affect the integrity of the cavern.

Shear zones are also known to contain a higher percentage of impurities than surrounding rock. An increase in impurities, together with variations in strength and solution properties, may affect the leaching of caverns to the desired shape and volume. In addition, shear zones may contain pockets of gas or brine under high pressure that could affect the safety of the drilling and leaching operations,

7.2.4 Methane and Hydrogen Sulfide

Caverns, vugs, and fractures may contain gas (both methane and hydrogen sulfide) under high pressure. High concentrations of methane gas are known to exist in the ground water associated with the cap rock on some salt domes, including West Hackberry. An accumulation of this gas either in a subsurface pocket or during water production or petroleum storage poses an explosive threat.

Hydrogen sulfide is known to be present in the cap rock of some domes. If the concentration is sufficiently high at West Hackberry dome, there could be serious corrosion problems with well casings, cement plugs, and other down-hole material related to the operation of,the SPR facility.

7.3 MAN-INDUCED HAZARDS

The hazards included in this category are situations or conditions created by man's activity in the vicinity of the salt dome. In some cases, man no longer has control over the situation, as in the existence of abandoned caverns. In other cases, man still retains at least some control over the condition that could pose a hazard. The potential hazards resulting from man's activities at the West Hackberry SPR Site are discussed below.

7.3.1 Gas Release

Leakage of stored petroleum products, especially those under pressure, poses a potential hazard. The leaks could occur either through rock discontinuities or by accidental discharge resulting from accidents or mechanical failure. Because of the presence of other gas storage facilities currently in operation at other sites at the West Hackberry dome, this is a potential hazard at the site.

7.3.2 Subsidence

In addition to natural subsidence (as discussed in Section 7.1.2) other potential causes of subsidence exist in the vicinity of the site. The most significant cause of subsidence is the withdrawal of fluids from the subsurface, including water, gas, and oil. This is a situation that can be directly controlled by man. Two types of subsidence can result from fluid withdrawals: area1 subsidence and differential subsidence. Some area1 subsidence already has occurred at the site. This is demonstrated by the dramatic increase in the size of Black Lake over the last 25 years (see Section 4.7). The amount of area1 subsidence that has actually occurred is unknown. This subsidence is probably the result of hydrocarbon and brine development around the perimeter of the dome.

To date, there has been relatively little demand placed on the shallow aquifers over the West Hackberry dome. If fluid development increases significantly, the accompanying depressurization-consolidation of the sediments will inevitably cause an increase in subsidence. A significant increase in subsidence in the vicinity of the site will increase the exposure to the flooding hazard (Section 7.1.3).

In some areas of the Gulf Coast region, area1 subsidence has been accompanied by differential subsidence across preexisting zones of weakness (non-tectonic fault planes) due to fluid withdrawal. This differential subsidence has resulted in collapsing or shearing of casing that crosses these fault planes. Area1 subsidence has occurred at the West Hackberry site, thus differential subsidence may also occur across faults at the site.

The abandoned caverns that were leached by Olin Corporation prior to SPR development present another potential subsidence hazard to the surface facilities at the site (Section 6.6.1). A sudden collapse of one of these caverns could propagate to the surface, creating a large, enclosed depression. The present brine pond at the site appears to overlie one of these caverns. There also is a possibility that Olin Corporation or its predecessors may have leached some of the halite zones within the cap rock, thus creating caverns in the cap rock that could lead to surface collapse.

7.3.3 Cavern Closure

There is a general problem of closure or convergence in storage caverns owing to residual stresses in the salt and the characteristic of the salts to deform plastically (creep) in response to imposed stresses (Section 6.4). An analysis of closure is beyond the scope of this investigation.

7.4 MITIGATING MEASURES

Aspects of the geometry, lithology, structure, and hydrology of the salt dome present hazards that can be more confidently avoided or mitigated with further study and evaluation. These hazards include: potential circulation and cementing problems due to composition and integrity of sediments and cap rock; loss of wells due to displacement along shear zones in the sediments, cap rock, and salt; potential failure or damage of surface structures resulting from collapsible soils; risk to stability and integrity of caverns in the salt due to inhomogeneities, faulting, and structural weaknesses in salt mass; leakage due to possible high porosity and permeability of shear zones: explosive threat from accumulation of methane gas; and potential corrosion of well casing, cement plugs, and other down-hole material due to hydrogen sulfide in cap rock.

7.4.1 Characterization Aspects

To aid in the definition of subsurface geometry, lithology, and hydrogeology of the West Hackberry dome structure, a coordinated exploratory program might be undertaken. The program would include a program of geophysics, drilling and sampling, and borehole logging.

a) High resolution reflection seismic surveys and micro-gravity surveys will assist in defining the boundaries of the dome and the locations of faults. This is particularly important along the northern edge of the dome in the cavern expansion area. Preliminary seismic programs were initiated in the latter stages of the Phase I characterization investigations to study the configuration of the northern edge of the dome. Micro-gravity surveys were conducted over the existing and expansion cavern areas. Refraction seismic surveys may be helpful to further define areas of structural concern near the periphery of the dome.

b) A drilling and sampling program will verify subsurface geometry in areas of concern; provide needed information on the lithology of cap rock and salt and on the permeability and geochemistry of fluids in the salt, cap rock, and sediments; and provide further information on the structural integrity of the salt and cap rock. Test holes can be further utilized as monitoring stations over the life of the project.

c) All boreholes should be logged in as great a detail as possible to continually update the structural, lithologic, and hydrologic models of the dome to facilitate additional design construction and operation of the project. Borehole logging should include:

1) Initial inspection and description of core and cuttings on site, supplemented by detailed descriptions in the laboratory. At least one full length core (to salt) should be obtained and inspected. Selected portions of other boreholes, such as at faults and contacts, should also be cored and the core inspected as described above.

2) Borehole geophysical logs to measure properties related to lithology (including soluble and insoluble portions), strength, and contained fluids of the sections drilled. Examples of geophysical logs that should be obtained for each borehole include resistivity, spontaneous potential, density, neutron, and caliper. For critical areas, borehole cameras should be considered.

7.4.2 Faulting

Faulting presents a hazard to operation of the West Hackberry storage facility. Potential displacement or shearing of cavern walls, surface and subsurface supply lines, and wells may result in significant operational delays and create leakages or other hazardous situations. To further identify locations of surface lineaments and potential faults, additional fault evaluation studies may be undertaken. These studies would include at least two phases:

a) Phase 1 - Detailed analysis, including computer enhancement, of high-resolution remote sensing imagery of the site and vicinity should be completed.

b) Phase 2 - Additional field verification of selected lineaments and detailed fault investigations, such as mapping, trenching, and test drilling, should be done as required. Age dating of Quaternary deposits should be carried out to establish the age of units displaced by the faults.

7.4.3 Abandoned Caverns

Existing abandoned caverns at the West Hackberry SPR Site present a possible hazard if they were to coalesce with new caverns, collapse, or otherwise lose integrity. To evaluate the possible influence of abandoned caverns on facilities within, and adjacent to, the site, a characterization of their locations, geometries, fluids, and effects on overlying sediments may be undertaken. An investigation program of re-entry drilling, logging, and testing may be warranted.

7i4.4 Flooding

Flooding presents a hazard to the West Hackberry SPR Site. A realistic prediction of the effects on continuing operation, safe shutdown, and protection of life and property is required. To better assess the flooding hazard, the results of an ongoing regional state-of-the-art evaluation of the loo-year hurricane surge by the Federal Emergency Management Administration can be applied to the site.

7.5 LONG-TERM MONITORING

7.5.1 Subsidence

Subsidence is an existing hazard to the West Hackberry SPR Site. Subsidence is known to occur around the dome to the extent that Black Lake is encroaching on the site facilities and access to the site could become imperiled in times of high water. Presently, there are no baseline data to establish the rate or extent of subsidence.

A program of subsidence monitoring at the site and vicinity. should include: 1) establishment and maintenance of first-order geodetic control network as described below: 2) preparation of a topographic map for the site facilities using new geodetic control; and 3) modeling of the predicted rates and magnitudes of area1 subsidence and differential subsidence and their potential effects on engineered structures at the site. In addition, detailed instrumentation, including tiltmeter arrays, may be necessary to monitor surface manifestation of cavern closures.

A geodetic monitoring network for the West Hackberry SPR Site and vicinity should be established and surveyed as soon as possible to provide the longest time period between repeat surveys. The primary purpose of the proposed network is to detect and monitor relative surface movements that may impact on the design and operation of the SPR facilities. The surface movements could result from: 1) continued uplift of the salt dome; 2) differential subsidence across non-tectonic faults; 3) subsidence due to fluid withdrawal, including oil, gasI and ground water; 4) injection and withdrawal of brine and stored liquified petroleum products from the caverns; and 5) cavern closure.

The monitoring network should be carefully planned and tied to the nearest available National Geodetic Survey horizontal and vertical control. The possibility of establishing a tidal benchmark to use as the basis for future subsidence monitoring should be considered. When the network is established, more benchmarks than are actually needed for the monitoring should be installed. This is to account for the probable destruction of some benchmarks during normal construction activities. Some of the benchmarks will require special design because of the marsh conditions.

The initial survey should include the establishment of both vertical and horizontal control. The network could, therefore, be used to accurately locate property lines, wells, and other surface structures. Because most of the expected surface movement at the site is vertical, repeat surveys will consist of leveling. The leveling will be first-order, class 1 leveling and should be done by the National Geodetic Survey (NGS) or subcontracted to firms capable of doing first-order work following NGS procedures.

The leveling should be repeated at least once a year to monitor subsidence. Rates calculated from the repeated leveling should be compared with estimated historical and geological subsidence rates for the area to evaluate whether or not there has been a significant change with time.

The hurricane storm-surge model should be periodically reviewed in conjunction with the results of the subsidence monitoring program to reevaluate the storm-surge hazard.

7.5.2 Faulting

Future surface facilities should be located to avoid surface faults and planning studies for proposed caverns and wells should evaluate the locations of fault planes and shear zones to avoid these structures to the extent possible.

7.5.3 Operational Conditions

Operation of oil storage facilities at the West Hackberry SPR Site presents a possible hazard to the development and use of water resources in the vicinity of the site. A water quality and gas monitoring program should be established to sample ground water and surface water at, and adjacent to, the site to:

1) Establish a water quality baseline for ground-water aquifers and surface-water bodies in the area;

2) Provide a basis to assess whether or not hazardous levels of methane and/or liquified gases have collected; and

3) Monitor for contamination of aquifers and surface-water bodies that may be the result of leakage of oil or brine from the storage caverns.

Wells should be drilled on-site to provide monitoring stations for gas and ground water. Water wells drilled by Welsh Drilling and Services, Inc., as water supply for their drilling operations, could be incorporated as stations in this monitoring program.

Methane gas presents a protentially hazardous operational problem at the West Hackberry SPR Site. An anomalously high flow of methane has been detected at the West Hackberry dome area. The methane tends to become entrained in ground water and is released during turbulent flow, as would occur during pumping operations. Storage facilites for ground water should provide for the venting of methane gas.

A retirement plan for the storage caverns that evaluates the long-term stability of the caverns and the long-term protection of man and the environment should be developed and implemented.

8.0 REFERENCES

1. Algermissen, S.T., 1969, Seismic risk studies in the United States: National Oceanic and Atmospheric Administration, U.S. Department of Commerce, p. 20.

2. Arman, A., 1977, Evaluation of collapsing soils: Consultants report to Parsons, Brinckerhoff, Quade and Douglass, New York, N.Y.

3. Balk, R., 1949, Structure of Grand Saline salt dome, Van Zandt County, Texas: American Association of Petroleum Geologists Bulletin, v. 33, p. 1791-1829.

4. Balk, R., 1953, Salt structure of Jefferson Island salt dome, Iberia and Vermillion Parishes, Louisiana: American Association of Petroleum Geologists Bulletin, v. 37, p. 2455-2474.

5. Barton, D.C., 1933, Mechanics of formation of salt domes with special reference to Gulf Coast salt domes of Texas and Louisiana: American Association of Petroleum Geologists Bulletin, v. 17, no. 9, p. 1025-1083.

6. Bishop, W.F., 1973, Late Jurassic contemporaneous faults in north Louisiana and south Arkansas: American Association of Petroleum Geologists Bulletin, v. 57, no. 5, p. 858-877.

7. Bornhauser, M., 1958, Gulf Coast tectonics: American Association of Petroleum Geologists Bulletin, v. 42, no. 2, p. 339-370.

8. Bruce, C.H., 1973, Pressured shale and related sediment deformation: mechanism for development of regional contemporaneous faults: American Association of Petroleum Geologists Bulletin, v. 57, no. 5, p. 878-886.

9. Caldwell, G.T., and Walker, W.H., 1979, Pumpage of water in Louisiana, 1975: Louisiana Department of Transportation and Development, Office of Public Works, Water Resources Special Report No. 2, 15 p.

10. Carver, R.E., 1968, Differential compaction as a cause of regional contemporaneous faults: American Association of Petroleum Geologists Bulletin, v. 52, no. 3, p. 414-419.

11. Coffman, J.L., and von Hake, C.A. Ws.), 1973, Earthquake history of the United States: U.S. Department of Commerce, Washington, D.C., Revised edition-through 1970, Publication 41.-l.

12. Davisson, M.T., 1977, Wave equation analyses-FEA projects: Consultants report to Parsons Brinckerhoff, Kavernen Bau-Und Betriebs-GMBH, New York, N.Y.

13. Dawson-Grove, G.E., 1968, The sonar caliper: Canadian Well Logging Journal, v. 1, no. 1, p. 7-13.

14. Docekal, J., 1970, Earthquakes of the stable interior with emphasis on the mid-continent: Ph.D. dissertation, University of Nebraska, Lincoln.

15. Domenico, P.A., 1972, Concepts and Models in Groundwater Hydrology: McGraw-Hill, New York, 405 p.

16. Dow Chemical U.S.A., 1973, Dowel1 sonar caliper for the measurement of underground cavities: Brochure produced by Dowel1 Division of Dow Chemical U.S.A., Tulsa, Oklahoma, 4 p.

17. Dow Chemical U.S.A., 1979a, Dowel1 sonar caliper survey# West Hackberry well no. 6-C, September 17, 1979: Report submitted to Texas Brine Corporation, by Dowel1 Division of Dow Chemical U.S.A., Tulsa, Oklahoma.

18. Dow Chemical U.S.A., 1979b, Dowel1 sonar caliper surveyl West Hackberry well no. 6-B, September 18, 1979: Report submitted to Texas Brine Corporation, by Dowel1 Division of Dow Chemical U.S.A., Tulsa, Oklahoma.

19. Dryer, W.E., 1974, Results of recent studies on the stability of crude oil and gas storage in salt caverns: Fourth Symposium on Salt, Northern Ohio Geological Society, v. 2, p. 65-92.

20. Fader, S.W., 1954, An analysis of contour maps of water levels in wells in southwestern Louisiana, 1952 and 1953: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works, Water Resources Pamphlet No. 1, 7 p.

21. Fenix and Scisson, Inc., 1973, Brine well evaluation, West Hackberry brine field: Report to Olin Corporation, Stamford, Connecticut, 83 p.

22. Fenneman, N.H., 1938, Physiography of Eastern United States, McGraw-Hill, New York, 714 p.

23. Goldman, M.I., 1952, Deformation, metamorphism, and mineralization in gypsum-anhydrite cap rock, Sulphur salt dome, Louisiana: Geological Society of America Bulletin, Memoir 50, 169 p.

24. Gulf Interstate Engineering Company, 1977a, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy, West Hackberry site, Cavern 6, 34 p., plus exhibits.

25. Gulf Interstate Engineering Company, 197713, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy I West Hackberry site, Cavern 7, 37 p., plus exhibits.

26. Gulf Interstate Engineering Company, 1977c, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy t West Hackberry site, Cavern 8, 26 p., plus exhibits.

27. Gulf Interstate Engineering Company, 1977d, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy r West Hackberry site, Cavern 9, 28 p., plus exhibits.

28. Gulf Interstate Engineering Company, 1977e, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy, West Hackberry site, Cavern 11, 24 p., plus exhibits.

29. Gulf States Utilities Company, 1974, Preliminary safety analysis report, Blue Hills station, Units 1 & 2: from Figure 2.5-2: Map of regional geology.

30, GUSSOW, W.G., 1968, Salt diapirism, importance of temperature and energy source of emplacement: Diapirism and Diapirs: American Association of Petroleum Geologists, Memoir No. 8, p. 16-52.

31. Halbouty, M.T., and Hardin, G.C., Jr., 1956, Genesis of salt domes of Gulf Coastal plain: American Association of Petroleum Geologists Bulletin, v. 40, no. 4, p. 737-746.

32. Halbouty, M.T., 1979, Salt Domes, Gulf Region, United States and Mexico: Gulf Publishing Company, Houston, 2nd edition, 561 p.

33. Hamblin, W.K., 1965, Origin of "reverse drag" on the down-thrown side of normal faults: Geological Society of America Bulletin, v. 76, no. 10, p= 1145-1164.

34. Hand, R.W., Stabler, F., and Jenkins, N., 1977, Exhibits and data for the approval of the use and development of two additional salt cavities, wells no. 10 and no. 11, West Hackberry salt dome, Cameron Parish, Louisiana: Louisiana Department of Conservation Docket No. SDS-4.

35. Hanna, M.A., 1953, Fracture porosity in Gulf Coast: American Association of Petroleum Geologists Bulletin, v. 37, p. 266-281.

36. Harder, A.H., 1960, The geology and ground-water resources of Calcasieu Parish, Louisiana: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works, Water-Supply Paper 1488, 102 p.

37. Harder, A.H., Whitman H.M., and Rogers, S.M., 1965, Methane in the fresh-water aquifers of southwestern Louisiana and theoretical explosion hazards: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works, Water Resources Pamphlet No. 14, 22 p.

38. Harder, A.H., Kilburn, C., Whitman, H.M., and Rogers, S.M., 1967, Effects of groundwater withdrawals on water levels and saltwater encroachment in southwestern Louisiana, Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works Water Resources, Bulletin No. 10, 56 p.

39. Hardin, F.R., and Hardin, G.C., Jr., 1961, Contemporaneous normal faults of the Gulf Coast and their relation to flexures: American Association of Petroleum Geologists Bulletin, v. 45, no. 2, p* 238-248.

40. Harris, D.L., 1958, An interim hurricane storm surge forecasting guide: U.S. Weather Bureau, National Hurricane Research Project, Report No. 32, p. 4.

22. Fenneman, N.H., 1938, Physiography of Eastern United States, McGraw-Hill, New York, 714 p.

23. Goldman, M.I., 1952, Deformation, metamorphism, and mineralization in gypsum-anhydrite cap- rock, Sulphur salt dome, Louisiana: Geological Society of America Bulletin, Memoir 50, 169 p.

24. Gulf Interstate Engineering Company, 1977a, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy, West Hackberry site, Cavern 6, 34 p., plus exhibits.

25. Gulf Interstate Engineering Company, 197713, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy, West Hackberry site, Cavern 7, 37 p., plus exhibits.

26. Gulf Interstate Engineering Company, 1977c, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy, West Hackberry site, Cavern 8, 26 p., plus exhibits.

27. Gulf Interstate Engineering Company, 1977d, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy, West Hackberry site, Cavern 9, 28 p., plus exhibits.

28. Gulf Interstate Engineering Company, 1977e, Solution cavern certificates of usability and integrity for the strategic petroleum reserve program of the Department of Energy, West Hackberry site, Cavern 11, 24 p., plus exhibits.

29. Gulf States Utilities Company, 1974, Preliminary safety analysis report, Blue Hills station, Units 1 & 2: from Figure 2.5-2: Map of regional geology.

30. Gussow, W.G., 1968, Salt diapirism, importance of temperature and energy source of emplacement: Diapirism and Diapirs: American Association of Petroleum Geologists, Memoir No. 8, p. 16-52.

31. Halbouty, M.T., and Hardin, G.C., Jr., 1956, Genesis of salt domes of Gulf Coastal plain: American Association of Petroleum Geologists Bulletin, V. 40, no. 4, p. 737-746.

32. Halbouty, M.T., 1979, Salt Domes, Gulf Region, United States and Mexico: Gulf Publishing Company, Houston, 2nd edition, 561 p.

33. Hamblin, W.K., 1965, Origin of "reverse drag" on the down-thrown side of normal faults: Geological Society of America Bulletin, v. 76, no. 10, p* 1145-1164.

34. Hand, R.W., Stabler, F., and Jenkins, N., 1977, Exhibits and data for the approval of the use and development of two additional salt cavities, wells no. 10 and no. 11, West Hackberry salt dome, Cameron Parish, Louisiana: Louisiana Department of Conservation Docket No. SDS-4.

35. Hanna, M.A., 1953, Fracture porosity in Gulf Coast: American Association of Petroleum Geologists Bulletin, v. 37, p. 266-281.

36. Harder, A.H., 1960, The geology and ground-water resources of Calcasieu Parish, Louisiana: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works, Water-Supply Paper 1488, 102 p.

37. Harder, A.H., Whitman H.M., and Rogers, S.M., 1965, Methane in the fresh-water aquifers of southwestern Louisiana and theoretical explosion hazards: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works, Water Resources Pamphlet No. 14, 22 p.

38. Harder, A.H., Kilburn, C., Whitman, H.M., and Rogers, S.M., 1967, Effects of groundwater withdrawals on water levels and saltwater encroachment in southwestern Louisiana, Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works Water Resources, Bulletin **No.** 10, 56 p.

39. Hardin, F.R., and Hardin, G.C., Jr., 1961, Contemporaneous normal faults of the Gulf Coast and their relation to flexures: American Association of Petroleum Geologists Bulletin, v. 45, no. 2, p* 238-248.

40. Harris, D.L., 1958, An interim hurricane storm surge forecasting guide: U.S. Weather Bureau, National Hurricane Research Project, Report No. 32, p. 4.

41. Harris-Galveston Coastal Subsidence District, 1979, Unnumbered Pamphlet, 8 p.

42. Hazzard, R.T., Blanpied, B.W., and Spooner, W.C., 1947, Notes on correlations of the Cretaceous of east Texas, south Arkansas, north Louisiana, Mississippi, and Alabama: 1945 Reference Report, Shreveport Geological Society, v. 2, p. 472-481.

43. Hershfield, D.M., 1963, Rainfall frequency atlas of the United States: U.S. Department of Commerce, Weather Bureau, Technical Publication No. 40.

44. Hicks, S.D., and Crosby, J.E., Undated, Trends and variability of yearly mean sea level, 1893-1972: NOAA Technical Memorandum, Unnumbered, 14 p.

45. Ho, F.P., Schwerdt, R.W., and Goodyear, H.V., 1975, Some climatological characteristics of hurricanes and tropical storms, Gulf and East Coasts of the United States, NOAA Technical Report NWSl5, p. 21.

46. Houston Lighting and Power Co., 1974, Preliminary safety analysis report, South Texas Project Units 1 and 2: Report submitted to Nuclear Regulatory Commission by Houston Lighting and Power Co., Houston, Texas.

47. Howe, H.V., Russel, R.J., McGuirt, J.H., and Craft, B.C., 1935, Reports on the geology of Cameron and Vermillion Parishes: Baton Rouge: Louisiana Geological Survey, Bulletin No. 6, 242 p.

48. Jacobs/D'Appolonia, 1979, Surge cavern feasibility study, West Hackberry, Bryan Mound, Bayou Choctaw: Report No. J/D-ROlO, unpublished report to Department of Energy, Strategic Petroleum Reserve Project Office.

49. Johnson, H.A., and Bredeson, P.H., 1971, Structural development of some shallow salt domes in Louisiana Miocene productive belt: American Association of Petroleum Geologists Bulletin, v. 55, no. 2, p* 204-226.

50. Jones, P.H., 1975, Geothermal and hydrocarbon regimes, northern Gulf of Mexico Basin: Proceedings of the First Geopressurred-Geothermal Energy Conference, Center for Energy Studies, University of Texas, p* 6-84.

51. Jones, P.H., Turcan, A.N., Jr., and Skibitzke, H.E., 1954, Geology and ground-water resources of

southwestern Louisiana: Baton Rouge: Louisiana Geological Survey, Bulletin No. 30.

52. Kreitler, C.W., 19.76, Lineations and faults, Texas coastal zone: Bureau of Economic Geology, University of Texas at Austin, Geology Report of Investigations 85.

53. Kupfer, D.H., 1962, Structure of Morton Salt Company Mine, Weeks Island salt dome, Louisiana: American Association of Petroleum Geologists Bulletin, v. 46, no. 8, p. 1460-1467.

54. Kupfer, D.H., 1970, Mechanism of intrusion of Gulf Coast salt: Third Symposium on Salt, Northern Ohio Geological Society, p. 25-66.

55. Kupfer, D.H., 1974a, Environment and intrusion of Gulf Coast salt and its probable relationship to plate tectonics: Fourth Symposium on Salt, Northern Ohio Geological Society, v. 1, p. 197-213.

56. Kupfer, D.H., 197413, Boundary shear zones in salt stocks: Fourth symposium on Salt, Northern Ohio Geological Society, v. 1, p. 215-225.

57. Law Engineering Testing Company, 1977a, Collapsing soil study: Consultants report to Parsons Brinckerhoff, Quade & Douglass, New York, N.Y.

58. Law Engineering Testing Company, 197733, Black Lake probing investigation: Consultants report to Parsons Brinckerhoff, Quade & Douglass, New York, N.Y.

59. Law Engineering Testing Company, 1977c, Report of seismic studies at FEA sites: Bryan Mound, Bayou Choctaw and West Hackberry: Consultants report to Parsons, Brinckerhoff, Quade & Douglass, New York, N.Y.

60. Londes, K.K., 1946, Porosity through dolomitization: American Association of Petroleum Geologists Bulletin, v. 30, no. 3, p. 305-318.

61. Louis Records & Associates, 1977, Well History, Department of Energy SPR Re-entry Well No. 7A: Louis Records report to Department of Energy.

62. Louis Records & Associates, 1978a, Well History, Department of Energy SPR Brine Disposal Well 1A: Louis Records report to Department of Energy.

63. Louis Records & Associates, 1978b, Well History, Department of Energy SPR Brine Disposal Well 1B: Louis Records report to Department of Energy.

64. Louis Records & Associates, 1978c, Well History, Department of Energy SPR Brine Disposal Well 1C: Louis Records report to Department of Energy.

65. Louis Records & Associates, 1978d, Well History, Department of Energy SPR Brine Disposal Well 1 Workover: Louis Records report to Department of Energy.

66. Louis Records & Associates, 1978e, Well History, Department of Energy SPR Brine Disposal Well 2A: Louis Records report to Department of Energy.

67. Louis Records & Associates, 1978f, Well History, Department of Energy SPR Brine Disposal Well 2B: Louis Records report to Department of Energy.

68. Louis Records & Associates, 1978g, Well History, Department of Energy SPR Brine Disposal Well 2C: Louis Records report to Department of Energy.

69. Louis Records & Associates, 1978h, Well History, Department of Energy SPR Brine Disposal Well 2D: Louis Records report to Department of Energy.

70. Louis Records & Associates, 1978i, Well History, Department of Energy SPR Brine Disposal Well 2E: Louis Records report to Department of Energy.

71. Louis Records & Associates, 1978j, Well History, Department of Energy SPR Cavern Well No. 6 Workover: Louis Records report to Department of Energy.

72. Louis Records & Associates, 1978k, Well History, Department of Energy SPR Re-entry Well No. 6A: Louis Records report to Department of Energy.

73. Louis Records & Associates, 19781, Well History, Department of Energy SPR Re-entry Well No. 6B: Louis Records report to Department of Energy.

74. Louis Records & Associates, 1978m, Well History, Department of Energy SPR Re-entry Well No. 6C: Louis Records report to Department of Energy.

75. Louis Records & Associates, 1978n, Well History, Department of Energy SPR Cavern Well No. 7 Workover: Louis Records report to Department of Energy.

76. Louis Records & Associates, 1978o, Well History, Department of Energy SPR Re-entry Well No. 7A Completion Supplement: Louis Records report to Department of Energy.

77. Louis Records & Associates, 1978p, Well History, Department of Energy SPR Re-entry Well No. 7B Completion Supplement: Louis Records report to Department of Energy.

78. Louis Records & Associates, 1978q, Well History, Department of Energy SPR Re-entry Well No. 8A: Louis Records report to Department of Energy.

79. Louis Records & Associates, 1978r, Well History, Department of Energy SPR Re-entry Well No. 8B: Louis Records report to Department of Energy.

80. Louis Records & Associates, 1978s, Well History, Department of Energy SPR Cavern Well No. 9 Workover: Louis Records report to Department of Energy.

81. Louis Records & Associates, 1978t, Well History, Department of Energy SPR Re-entry Well No. 9A: Louis Records report to Department of Energy.

82. Louis Records & Associates, 1978u, Well History, Department of Energy SPR Re-entry Well No. 9B: Louis Records report to Department of Energy.

83. Louis Records & Associates, 1978v, Well History, Department of Energy SPR Re-entry Well No. 11A: Louis Records report to Department of Energy.

84. Louis Records & Associates, 1979a, Well History, Department of Energy SPR Brine Disposal Well 1B Workover: Louis Records report to Department of Energy.

85. Louis Records & Associates, 1979b, Well History, Department of Energy SPR Cavern Well No. 8 Workover: Louis Records report to Department of Energy.

86. Louis Records & Associates, 1979c, Well History, Department of Energy SPR Cavern Well No. 11: Louis Records report to Department of Energy.

87. Louis Records & Associates, 1979d, Well History, Department of Energy SPR Re-entry Well No. 11B: Louis Records report to Department of Energy.

88 Louisiana Department of Transportation and Development, 1976, Floods in Louisiana: magnitude and

frequency: Louisiana Department of Transportation and Development and U.S. Geological Survey, Baton Rouge, p. 297-316.

89. Muehlberger, W.R. 1960, Internal structures and mode of uplift of the Grand Saline salt dome, Van Zandt County, Texas, U.S.A.: Structure of the Earth's Crust and Deformation of Rocks, Twenty-first International Geologic Congress, Report 18, p. 28-33.

90. Murray, G.E., 1961, Geology of the Atlantic and Gulf Coastal Province of North America: Harper and Brothers, New York, 692 p.

91. Murray, G.E., 1966, Salt structures of Gulf of Mexico basin - a review: American Association of Petroleum Geologists Bulletin, v. 50, no. 3, p. 439-478.

92. Nettleton, L.L., 1934, Fluid mechanics of salt domes: American Association of Petroleum Geologists Bulletin, v. 18, p. 1175-1204.

93. New Orleans Geological Society, 1961, Salt domes of southwest Louisiana.

94. Ocamb, R.O., 1961, Growth faults of south Louisiana: Gulf Coast Association of Geological Societies, Transactions, v. 11, p. 139-175.

95. Parker, T.J., and McDowell, A.N., 1955, Model studies of salt dome tectonics: American Association of Petroleum Geologists Bulletin, v. 39, no. 12, p. 2384-2470.

96. Parsons Brinckerhoff Kavernen Bau-Und Betriebs-GMBH, 1978a, Strategic Petroleum Reserve Program leach/fill study, West Hackberry, Louisiana: Report submitted to Department of Energy, Harahan, Louisiana.

97. Parsons Brinckerhoff Kavernen Bau-Und Betriebs-GMBH, 1978b, Strategic Petroleum Reserve core drilling program, West Hackberry, Louisiana: Report submitted to the Department of Energy I Harahan, Louisiana.

98. Parsons Brinckerhoff Kavernen Bau-Und Betriebs-GMBH, 1978c, Supplemental geotechnical engineering report: Department of Energy, Strategic Petroleum Reserve Project, West Hackberry, Louisiana, 31 p.

99. Parsons Brinckerhoff Kavernen Bau-Und Betriebs-GMBH, 1978d, Geotechnical report for SPR site: Consultants report to Department of Energy.

100. Poland, J.F., and Davis, G.H., 1969, Land subsidence due to withdrawal of fluids: Reviews in Engineering Geology, Geological Society of America Bulletin, v. II, p. 187-269.

101. Press, F., and Siever, R., 1974, Earth: W.H. Freeman and Company, San Francisco, 945 p.

102. Quarles, M.W., Jr., 1953, Salt-ridge hypothesis on origin of Texas Gulf Coast type of faulting: American Association of Petroleum Geologists Bulletin, v. 37, no. 3, p. 489-508.

103. Richter-Bernburg, G., 1972, Saline deposits in Germany - a review: in Geology of Saline Deposits, Unesco Symposium atxnnover, p. 275-287.

104. Schuchert, C., 1935, Historical Geology of the Antillean-Caribbean region: John Wiley and Sons, New York, 811 p.

105. Scott, K.R., Hayes, W.E., and Fietz, R.P., 1961, Geology of the Eagle Mills Formation: Gulf Coast Association of Geological Societies, Transactions, v. 11, p* 1-14.

106. Seglund, J.A., 1974, Collapse-fault systems of Louisiana Gulf Coast: American Association of Petroleum Geologists Bulletin, v. 58, no. 12, p. 2389-2397.

107. Shlemon, R.J., 1973, Atchafalaya BayI Louisiana: Regional subsidence and contemporary delta formation: Gulf Coast Association of Geological Societies, Transactions, v. 23, p. 22-26.

108. Stover, C.W., Reagor, B.G., and Algermissen, S.T., 1979, Seismicity map of the United States: U.S. Geological Survey, Map MF-1081.

109. Taylor, R.E., 1938, Origin of the caprock of Louisiana salt domes: Louisiana Geological Survey, Bulletin 11, 191 p.

110. U.S. Army Corps of Engineers, New Orleans District, 1970a, Type 5 Flood insurance study, Louisiana Gulf Coast: U.S. Department of Housing and Urban Development, Federal Insurance Administration, p. l-4, Plates l-6.

111. U.S. Army Corps of Engineers, Galveston District, 1970b, Flood insurance study, Texas Gulf Coast, Sabine Lake to Matagorda Bay, Vol. I: U.S. Department of Housing and Urban Development, Federal Insurance Administration, p. l-4.

112. U.S. Department of Commerce, Coast and Geodetic Survey, 1968, Vertical Control Data of 1965, Line 101, near Hackberry Louisiana.

113. U.S. Department of Housing and Urban Development, Federal Insurance Administration, 1970, Interim Revision 1974. FIA official flood hazard maps of Cameron Parish, Louisiana, Scale 1:62,500, 4 plates.

114. U.S. Department of Housing and Urban Development, Federal Insurance Administration, 1978, Flood insurance study Calcasieu Parish, Louisiana (Unincorporated areas), p. 6.

115. U.S. Geological Survey, 1977, Water resources investigations in Louisiana: Bibliography and summary of available data, p. l-6.

116. U.S. Geological Survey, 1979, Water situation in Louisiana, 8 p.

117. U.S. Weather Bureau, 1963 [see Hershfield].

118. Usiglio, J., 1849, Analyse de l'eau de la Mediterranee sur la tote de France: Annales de Chimestrie et de Physique, serie 3, p. 92-172.

119. Walker, C.W., 1974, Nature and origin of caprock overlying Gulf Coast salt domes: Fourth Symposium on Salt, Northern Ohio Geological Society, v. 1, p* 169-195.

120. Wallace, W.E., Jr., 1944, Structure of south Louisiana deep seated domes: American Association of Petroleum Geologists Bulletin, v. 28, p. 1249-1312.

121. Whelply, F.V., 1979, West Hackberry site work over procedures, Cavern no. 6: Texas Brine Corporation, 23 p.

122. Woodward-Clyde Consultants, 1980a, Assessment of Potential Environmental Impacts of Geopressured Methane Development: unpublished report submitted to Gas Research Institute.

123. Woodward-Clyde Consultants, 1980b, Strategic Petroleum Reserve core logging program, West Hackberry, Louisiana: Consultant's report to Sandia National Laboratories.

124. Woodward and Lundgren, 1974, Detection and evaluation of differential surface displacement in the Texas Gulf Coast region: Consultant's report to Brown and Root, Inc., Houston, Texas.

125. World Oil, 1950, Current Outlook Section, West Hackberry production: v. 130, no. 7, p. 98.

126. Zack, A.L., 1971, Ground-water pumpage and related effects, southwestern Louisiana, 1970: Department of Conservation, Louisiana Geological Survey and Louisiana Department of Public Works, Water Resources Pamphlet No. 27, 33 p.

APPENDIX A

TABULATION OF CAVERN HOLES, EXPLORATION BORINGS, AND WATER WELLS UTILIZED IN THIS STUDY

APPENDIX A

List of Tables

Explanation for Tables

Hole Numbering System

Cavern Holes	-	DOE designations
Exploration Holes	-	Section number and sequential numbering
Water Wells	-	State of Louisiana designation

APPENDIX A

TABULATION OF CAVERN HOLES, EXPLORATION BORINGS, AND WATER WELLS UTILIZED IN THIS STUDY

Elevation of datum points BB (base of "Brc sand), TC (top of cap rock), and TS (top of salt) are elevations related to mean sea level. In each case, the Kelley bushing was used as reference elevation on the log, unless noted otherwise. Also, unless specifically noted on the log, the Kelley bushing height above ground surface was considered to be 15 feet on holes with a depth of less than 5,000 feet and 20 feet for holes in excess of 5,000 feet.

TABLE A-1
CAVERN HOLES

Base Map #	Operator & Lease Name	Completion Date	BB/ TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
DOE #6	Olin C.N. Ellender #5 Serial #32393	10-46	/-1568/-1919 2640'		3650'FSL & 790 FEL Sec 20
DOE #6A	DOE SPR RE 6A	9-21-78	-592/-1562/-1965		3902'N and 65'W of SE corner Sec 20
DOE #6B	DOE SPR RE 6B	7-16-78	/-1568/-1919 3242' (salt)		3947'N and 501'W of SE corner Sec 20
DOE #6C	DOE SPR RE 6C	8-4-78	/-1580/-2045 3355' (salt)		3947'N & 800'W of SE corner Sec 20
DOE #7	Olin C.N. Ellender #3 Serial #31739	6-46	/-1520/-1935		3254.2'N & 333.3'E of SW corner Sec 21
DOE #7A	DOE SPR RE 7A	7-27-78	-555/-1520/-1928 2550' (salt)		
DOE #7B	DOE SPR RE 7B	8-3-78	-523/-1518/-1970 2430' (salt)		
DOE #8	Olin C.N. Ellender #4 Serial #32032	8-46	/-1510/-1961		2548.6'N & 419.9' W of SE corner Sec 20
DOE #8A	DOE SPR RE 8A	6-1-78	-525/-1510/-2010 2451' (salt)		
DOE #8B	DOE SPR RE 8B	6-23-78	-525/-1485/-1980 2450' (salt)		
DOE #9	Olin C.N. Ellender #6 Serial #32661	1-47	/-1520/-2000		2952'FSL & 926'FEL Sec 20

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

TABLE A-1
CAVERN HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Interval Plugging and Aban. Date	Location
DOE #9A	DOE SPR RE 9A	3-19-78	/-1520/-2000 3212' (salt)		
DOE #9B	DOE SPR RE 9A	4-28-78	-530/-1537/-2016 3217' (salt)		
DOE #11	Olin JC Ellender #4 Serial #86594	9-61	/-1560/-2030		639'FEL & 150'FSL Sec 21
DOE #101			/-1555/-2000[3]		1500 FSL & 1850 FEL
DOE #106			/-1535/-1980[3]		350 FSL & 2250 FEL

[1] BB = Ba of "B" Sand; TC = Top of Ca Rock; TS = Top of Salt [3]Estimate

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Logging Interval Plugging and Aban. Date	Location
16-1	Stanolind School Bd. "A" 30	7-51	-1183/-1940/ 6688'		4730'E & 2620'N SW corner Sec 16
16-2	Duval Potash Co. Stanolind School Lease D-1	9-56	-763/ / 2107' (anhy)	-10', 1919-2019 9-56	200 N & 1620 W SE corner Sec 16
16-3	Pan Am C.P.S.B. R/A "A" #35 Serial #116405				1350'FSL & 2250'FWL Sec 16
16-4	Pan Am C.P.S.B. R/A "A" #38 Serial #126201				2830'FNL & 1220'FEL Sec 16
16-5	Stanolind C.P.S.B. R/A #16	7-36	/ /-3359 3379'	7-36	1350'N & 2190'E SW corner Sec 16
16-6	Stanolind C.P.S.B. R/A #17 Serial #19164	12-36	5750'	1919-2019' 2675-3050' 12-36	1650'N & 2190'E SW corner Sec 16
16-7	Stanolind C.P.S.B. R/A #18 Serial #19628	4-37	6010'		2330'N & 2440'E SW comer Sec 16
16-8	Stanolind C.P.S.B. R/A #19 Serial #19552	7-37	-5360 (Salt)	1892-1992' 2244-2344' 7-37	3015'E & 2595'N SE corner Sec 16
16-9	Yont-Lee Oil Co. School Section #12 Serial #15631	2-33	/ /-4974 4694' (salt)	2-33	2330' FWL & 1460' FSL Sec 16
16-10	Yont-Lee Oil Co. School Board #13 Serial #15749	3-33	3598' (anhy)	3-33	1710'FSL & 2230'FWL Sec 16

[1] BB = Base of "B" Sand; TC = Top Of Cap Rock; TS = Top of Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
16-11	Yont-Lee Oil Co. School Land #14 Serial #16724	7-34	/ /-5393 5413' (salt)		1070'S & 435'W NE corner SW/4
16-12	Yont-Lee Oil Co. School Land #15	9-35	/ /-4950 7660' (salt)	9-35	1160'S & 715'W NE corner SW/4 Sec 16

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB/ TC/ TS[1] / Total Depth	Plugging Intervals / Plugging and Aban. Date	Location
17-1	Pan Am Gulf Land R/A "B" #52 Serial #68243	11-57	-930/ /-5300[2] 5366'	50-100' 1933-2273' 11-57	20'FNL & 3650'FEL Sec 17
17-2	Pan Am State Lease 42 #69 Serial #38005	1-64	8629'		2400'FSL & 2458'FEL Sec 17
17-3	Pan Am State Lease 42 #94 Serial #62221	9-56	6823'		135'FSL & 4800'FEL Sec 17
17-4	Pan Am State Lease 42 #95 Serial #45358	10-56	6717'	5684-6557' 4-57	430'FSL & 4800'FEL Sec 17
17-5	Pan Am State Lease 42 #98-D Serial #60357	6-58	8334'		1240'FSL & 4870'FEL Sec 17
17-6	Pan Am State Lease 42 #100-D Serial #62139	6-56	8204'	7285-7090'	1415'FSL & 4220'FEL Sec 17
17-7	Pan Am State Lease 42 #103 Serial #62735	9-56	8010'	15-110' 1800-2000' 7030-7357' 12-69	1535'FSL & 3560'FEL Sec 17
17-8	Pan Am State Lease 42 #105 Serial #63959	1-57	6615'	6403' 4-61	870'FSL & 4270'FEL Sec 17

[1] BB = Base of "B" Sand; TC = Top Of Cap Rock; TS = Top of Salt
[2] No Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
18-1	Pan Am State Lease 42 #69 Serial #30191	2-45	9108'	Collapsed casing at 8246' 9-68	1234'FSL & 6554'FEL Sec 17
18-2	Pan Am State Lease 42 #71 Serial #31441	1-46	8944'	15-115' 1900-2100' 7500-7800' 12-69	954'FSL & 7829'FEL Sec 17
18-3	Pan Am State Lease 42 #103 Serial #62735		8002'	245-6750' 6-70	1040'FSL & 5500'FEL Sec 17
18-4	Pan Am State Lease 42 #106	2-57	6774'		430'FSL & 5490'FEL Sec 17

[1] BB = Base of "B" Sand; TC = Top of Cap Rock: TS = Top of Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals: BB / TC / TS[1] Total Depth	Plugging Intervals: Plugging and Aban. Date	Location
19-1	Stanolind State Lease 42 #87	11-50	/ /-6251[2] 6251'		1460'FEL & 375'FNL Sec 19
19-2	Stanolind State Lease 42 #88	12-50	-880/ /-2401 6074'		1900'FEL & 925'FNL Sec 19
19-3	Amoco Gulf Land "A" R/A "C" #196	8-73	/-2550/-2700 4156'		3275'FEL & 860'FSL Sec 19
19-4	Pan Am Gulf Land "A" R/A C #110 Serial #97830	8-63	/ /-3770 4334'	35-85', 1883-2083', 3350-3550' 8-63	1567'FSL & 1450'FWL Sec 19
19-5	Pan Am State Lease 42 #70 Serial #35204	3-48	8570'	100-200' 1800-2000' 3350-3600' 3-70	875'FNL & 9074'FEL Sec 20
19-6	Pan Am State Lease 42 #90 Serial #42624	1-51	-835/ /-3555 4972'	0-50' 9-52	970'FNL & 6120'FEL Sec 20
19-7	Pan Am State Lease 42 #92 Serial #43308	6-51	/ /-4890 4928'	0-50' 9-57	400'FNL & 5300'FEL Sec 20
19-8	Pan Am State Lease 42 #93 Serial #43637	7-51	6088'	0-50' 9-57	1800'FNL & 8380'FEL Sec 20
19-9	Pop. Oil Co. JC Ellender #1 Serial #15265	8-32	/-2301/-2401 2430'	8-32	617'N & 931'W SE corner of NE/4 Sec 19
19-10	Pop. Oil Co. Yont-Lee #1 Serial #15904	4-34	3660'	4-34	3996'W & 100'N SE corner of Sec 19

[1] **BB = Base** of "B" Sand; **TC** = Top of Cap Rock; **TS** = Top of Salt [2] **No** Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals: BB/ TC / TS[1] / Total Depth	Plugging and Aban. Date	[illegible]
19-11	Freeport Sulfur Co. JM Vincent #3 Serial #29493	7-44	/-1730/ 1990'	7-44	795'FSL & 1120'FEL Sec 19
19-12	Pop. Oil Co. JC Ellender #1				830'FWL & 3650'FSL Sec 19
19-13	Freeport-Sulphur D. Kaough #3	7-44	1990'		1070'FEL & 770'FSL Sec 19

BB = Base of "B" Sand; TC = Top of Cap Rock; TS = of Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Interval Plugging and Aban. Date	Location
20-1	Olin C.N. Ellender #2 Serial #30481	5-45	 2152'	11-45' 350-450' 1-48	294'S & 114'E NW corner SE/4 NE/4 Sec 20
20-2	Union Sulfur A.M. Barbe #1	1-27	 1645' (anhy)	1-27	1655'FEL & 1500'FSL Sec 20
20-3	Olin #3 J.C. Ellender #1	2-34	/-1488/-2002 1900'	0-50' 1050-1200' 4-54	50'W & 50'S NE corner SE/4 SE/4 Sec. 20
20-4	Pan Am Agnes Lowry #1 Serial #126845	11-68	/-1530/-1990 1595' (caprock)	25-50' 1440-1450' 12-68	2300'FSL & 900'FEL Sec 20
20-5	Freeport Sulfur C.P. Ellender #1 Serial #29408	6-44	/-1659/ 1645' (anhy)	6-44	510'S & 1785'W from center Sec 20
20-6	Olin Olin Fee #12 Serial #155377	10-77	/-1632/-2060 2670'	Brining	195'W & 270'S of NE corner NW/4 SW/4 Sec 20
20-7	Olin Olin Fee #13	10-77	-610/-1583/-2040 4600'	Brining	195'W & 660'S of NE corner NW/4 SW/4 Sec 20
20-8	Olin Olin Fee #14 Serial #155579	9-77	/-1588/-2050 5025'	Brining	195'W & 1050'S of NE corner NW/4 SW/4 Sec 20
20-9	Freeport Sulfur J.C. Ellender #1 Serial #29447	6-44	/-2042/ 1645'	6-44	3750'FSL & 330'FWL Sec 20

[1] BB = Base of "B" Sand; TC = Top Of Cap Rock; TS = Top of Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB/ TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
20-10	Freeport Sulfur Hanszen #1 Serial #29429	6-44	/-1690/-2060 1775'	512-612, 1601-1701 6-44	510'E & 1015'N of center Sec 20
20-11	Carrl Oil Et Al J.C. Ellender #2	12-54	-720/-1732/ 1902'	12-54	2840'FSL & 100'FWL Sec 20
20-12	Olin A. Little Serial #16287	9-33	3003' (salt)	9-33	1375'E & 2037'N SW corner Sec 20
20-13	Olin C.N. Ellender #7 Serial #67841	7-58	1525'	0-10' 1050-1250' 7-58	50'W & 50'S NE corner SE/4 SE/4 Sec 20
20-14	Olin #4 C.N. Ellender #1 Serial #16617	6-34	/ /-2008 1850'	0-50' 1105-1205' 3-54	279.1'W & 50'N SE corner NE/4 SE/4 Sec 20
20-15	Union Sulphur J.C. Ellender #1	1-27	1680'		3050'FSL & 1380'FWL Sec 20
20-16	Union Sulphur J.C. Ellender #2				3050'FSL & 1660'FWL Sec 20
20-17	Freeport Sulphur Carrl Oil #1	6-44	7247'		4180'FSL & 355'FWL Sec 20
20-18	Stanolind Calcasieu Nat'l Bank #1				1215'FSL & 950' FWL Sec 20
20-19	Union Sulphur C. N. Ellender #1	1-27	1639'	1-27	1215'FEL & 1365'FSL Sec 20

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

TABLE A-2
EXPLROATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Interval Plugging and Aban. Date	Location
21-1	Carrl Oil Et Al J.C. Ellender #1	12-54	530/-1520/ **1554'**	12-54	2840'FSL & 100'FWL Sec 21
21-2	Union Sulfur #1		**1605'**		2740'FSL & 1650'FWL Sec 21
21-3	Union Sulfur Gulf Land A #2	8-24	**2052'**	8-24	356'FNL & 830'FWL Sec 21
21-4	Olin #1 Granger #1 Serial #16618	3-34	/-1534/ **2655'**	1466-1566' 6-48	511'N & 167'E SW corner NE/4 SW/4 Sec 21
21-5	Olin #5 J.C. Ellender #2 Serial #29320	5-46	**1955'**	600-700' 6-48	210'N & 572'W SE corner NW/4 SW/4 Sec 21
21-6	Olin #2 J.C. Ellender #3 Serial #29540	7-34	**2600'**	800-900' 5-48	*572 'W & 310'N SE corner NW/4 SW/4 Sec 21 +1980 FSL & 1400 FWL Sec.21
21-7	Cities Service CSO Fee #9	10-69	/ **/-2048**	Storage	200'W & 1100'N SE corner SW/4 SE/4 Sec 21 per agreement
21-8	Cities Service CSO Fee #10			Storage	750'FSL & 1300'FEL Sec 21
21-9	Pan Am B. Lyons Palmer Serial #126782	12-68	-574/ / **1612'**	12-68	520'FSL & 500'FWL Sec 21
21-10	Cities Service CSO Fee #7	7-69	/ /2055	Storage	200'W & 700'N SE corner SW/4 SE/4 Sec 21

* Location as it appears on completion report

\+ Location on plate 1 based on information supplied by Olin Corp. and is located on map supplied by the Louisiana Department of Conservation, Lake Charles, LA.

[1] **BB = Base of "B" Sand; TC = Top of Cap Rock; TS Top of Salt**

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
21-11	Freeport Sulphur TJ Plauche #1	8-44	1678'		148'FSL & 2580'FWL Sec 21
21-12	Carrl Oil Jaubert Bros. #1 Serial #54574	1-55	-510/ / 1573'	0-30' 64-164' 650-750' 1-55	1422'FEL & 1000'FSL Sec 21
21-13	Freeport Sulfur C.N. Ellender #1 Serial #29532	6-44	/-1551/ 1645'	1551-1585' 6-44	300'S & 800'E SW corner NW/4 NW/4 Sec 21
21-14	Freeport Sulfur Jaubert et al #1 Serial #29603	8-44	/-1530/2040 1678'	8-44	134'N & 55'W SW corner SW/4 Sec 21
21-15	Sutton Joint Account Porter Ellender #1 Serial #53720	12-54	-490/-1640/ 1560'	12-55	950'W & 50'S NE corner SE/4 SE/4 Sec 21
21-16	Sutton Joint Account Porter Ellender #2 Serial #56997	12-54	-526/-1660/-2110[3] 1691'	12-55	1220'N & 50'W SE corner Sec 21
21-17	Stanolind Gulf Land "A" #2	8-24	2052'		830'FWL & 330'FNL Sec 21
21-18	Pan Am N.P. Ellender #1 Serial #124813	10-68	-580/-1690/ 1744'		330'N & 800'W SE corner Sec 21
21-19CS	Yant Lee Gulf Land No. 1	5-22	/-1561/ 1905'		500' FNL & 1600 FEL

1 BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt
3 Estimate

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] / Total Depth	Plugging Intervals / Plugging and Aban. Date	Location
22-1	Duval Potash & Sulfur Co. Gulf Land D #2 Serial #62610	4-42	/-2175/-2205[3] 3699'	0-10, 178-278, 750-850 4-42	630'FNL & 1575'FWL Sec 22
22-2	Shallow Oil Co. Lacy #1 Serial #12238	11-28	1715'	11-28	842'N & 50'E SW corner Sec 22
22-3	Yont-Lee Oil Co. Lacy #2 Serial #13112	11-29	3719' (heaving sh.)	11-29	1280'E & 50'N SW corner Sec 22
22-4	Yont-Lee Oil Co. Lacy #3 Serial #13141	11-29	3297' (sand)	11-29	1280'E & 460'S NW corner Sec 22
22-5	Sutton Joint Account Mary Duhon #1 Serial #15447		3222'		12'E & 1547'N SW corner SW/4 Sec 22
22-6	Yont-Lee Gulf Land #3	3-23	/-1656/2106 2130'		1600' FNL & 1480' FWL Sec 22
22-7	Gulf Refining Co. Lacy #2 Serial #21313	2-13	1849'	2-13	300'N & 160'E SW corner Sec 22
22-8	Grady Roper Drilling Cont. AB McCaine #1 Serial #66310	6-57	2858' (sh. Lm)	0-25' 2771-2821' 3-73	1345'FSL & 1969'FWL Sec 22
22-9	Stanolind Carter & Sweeney	9-38	3547'		300'FSL & 50'FWL Sec 22

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

[3] Estimate

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB/ TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
22-10	Sutton Joint Account Robert Ellender #2 Serial #69428	2-58	5714'	0-20' 4300-4400' 12-63	330'S & 660'E NW corner SW/4 SE/4 Sec 22
22-11	Trice Production Co. Francis Lacy #1 Serial #60422	2-56	/ /2191	2-56	1220'FWL & 663'FSL Sec 22
22-12	Union Sulphur Gulf Land "C" #1		1779'		890'FWL & 1900'FSL Sec 22
22-13	E.C. Bolton Lacy #2 Serial #65133	2-57	/-1960/ 1994'		50'N & 350'W SE corner SW/4 SW/4 Sec 22
22-14			/-1896/-2046		2420 FNL & 2550 FWL Sec 22
22-15CS	Operator Unknown Lease name unknown		/-1676/-2126		1640 FSL & 750 FWL Sec 22

[1] BB = Base of "B" Sand; TC = Top of C Rock; TS = Top of Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
27-1	Nat'l Exploration Co. Hanszen #2 Serial #150103	9-75		Pumping	1000'FNL & 580'FWL Sec 27
27-2	Pan Am Porter Ellender #1 Serial #110364	8-65	7147'	50-125' 1300-1500' 8-65	200'N & 450'E SW comer SE/4 NW/4 Sec 27
27-3	Draper Goodale Gulf Noble #1 Serial #94637	4-63	8525'	0-20' 1386-1536' 7850-7950' 4-63	1962'FSL & 2327'FWL Sec 27
27-4	D.D. Filman F. Lacy #1 Serial #27353	4-42	3699'	570-640' 4-42	360'FNL & 990'FWL Sec 27
27-5	Fertitta & Co. Porter Ellender #1 Serial #55448	4-55	5522'	0-10', 1000-1125' 4150-4297' 2-56	170'FNL & 167'FWL Sec 27
27-6	Freeport Sulfur Francis Lacy #1 Serial #29596	8-44	/-1940/ 2102'	8-44	460'FNL & 75'FWL Sec 27
27-7	O.C. Garvey Porter Ellender #1 Serial #26541	11-41	8058' (shale)	0-1009' 11-41	330'N & 330'W of center Sec 27
27-8	Michael T. Halbouty Noble Gulf #1 Serial #64963	2-57	6785' (shale)	2-57	185'FNL & 75'FEL NW/4 SW/4 Sec 27

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals: BB/ TC / TS[1] Total Depth	Plugging and Aban. Date	Location
27-9	Michael T. Halbouty Nettie Thorn #1 Serial #66958	12-56	6133' (shale)		1658'E & 25'N SW corner NW/4 Sec 27
27-10	Michael T. Halbouty Nettie Thorn #2 Serial #64313	12-56	6307' (shale)		8455'S & 515'W NW corner SW/4 Sec 27
27-11	Yont-Lee Oil Co. Lacy #1 Serial #12967	10-29	3438' (shale)	10-29	1280'E & 180'S NW corner Sec 27
27-12	Yont-Lee Oil Co. Lacy #C-4 Serial #13802	7-30	3392' (shale)	7-30	981'FWL & 1137'FNL Sec 27
27-13	Sutton Joint Account Laura Duhon Serial #64794	1-57	/ /-3600[2] 3612'		1553'S & 130'E NW corner Sec 27
27-14	Sutton Joint Account R.D. Patrick Hr. Serial #63740	1-57	3500'		1420'S & 100'E NW corner Sec 27
27-15	BT Denny Trustee JH Duhon #1 Serial #16624	4-34	3361' (clean sd)		148'S & 467'E NW corner SW/4 NW/4 Sec 27
27-16	Sailers Well Serv. Co. Hansen Et Al #1 Serial #63453	12-58	3394'	0-10' 3150-3250' 12-66	1195'FNL & 50'FWL Sec 27
27-17	Sailers Well Serv. Co. Frances Lacey #2 Serial #72568	10-58	3394'	0-25' 3240-3250' 12-64	285'FNL & 1220'FWL Sec 27

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt
[2] No Salt

TABLE A-2
EXPLORATION HOLES

		Completion Date	Plugging Intervals BB/ TC / TS[1] Total Depth	Plugging and Aban. Date	Location
27-18	WT Burton Porter Ellender #1 Serial #20260	11-37	5499' (shale)	3-38	150'FNL & 500'FWL Sec 27
27-19	Stanolind Bolton #1	2-30	1078		210'FNL & 530'FWL Sec 27
27-20	EC Bolton Lacy Et Al #3 Serial #66075	5-57	552/ / 3420'		100'E & 450'N SW corner SE/4 NW/4 Sec 27

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB/ TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
28-1	Hurt O'Meara Porter #1	3-57	6010'		1485'FSL & 178'FEL Sec 28
28-2	Texkan Benchley #1	9-56	-603/ / 3514'	0-10,3034-3134' 5-63	1640'S & 515'W NE corner Sec 20
28-3	Wentworth & Laub Gray Et Al #2	3-58	/-1990/ 4010'	0-20,100-200' 500-600' 3-58	1963'FNL & 1977'FEL Sec 28
28-4	Texkan AM Barbe #1	12-55	-555/ / 3501'		1845'S & 965.4'W NE corner Sec 28
28-5	Wentworth & Laub Gray Et Al #1	12-57	-550/ / 3229'		1963'FNL & 1577'FEL Sec 28
28-6	Texkan Herbert #1	11-56	-613/ / 3514'		1920'S & 735.6'W NE corner Sec 28
28-7	Texkan Benchley #2		-570/ / 3515'		3050'FSL & 1160'FEL Sec 28
28-8	Barnett Serio Expl. Co. R. Vincent Estate #1	11-69	4250'		130'S & 150'E NW corner SE/4 Sec 28
28-9	Barnett Serv. Expl. Duhon #1	11-69	3968'		230'S & 400'E NW corner Sec 4-Sec 28
28-10	Ballard & Cordell F. Reed #1	3-74	4409'		2190'N & 2460'W SE corner Sec 28
28-11	Berry Oil Cora Lyons #1	9-38	-555/ / 3533'	9-38	150'S & 160'E NW corner SE/4 SW/4 Sec 28
28-12	Pan Am Ray Duhon #1 Serial #126938		2042'		1000'FNL & 1500'FEL Sec 28

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

)

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals: BB[1]/ TC / TS Total Depth	Plugging and Aban. Date	Location
28-13	Pan Am Mammie L. Gray #2 Serial #127228	12-68	530/ / 2092'	12-68*	680'FNL & 1175' FEL Sec 28
28-14	Pan Am Mammie L. Gray #1 Serial #125960	11-68	/-1870/ 1903'	11-68*	530'FNL & 850'FEL Sec 28
28-15	Pan Am Mammie L. Gray #3 Serial #127229	12-68	504/-1690/ 1751'	12-68*	270'FNL & 1050'FEL Sec 28
28-16	Pan Am Mammie L. Gray #4 Serial #127377	12-68	/-1880/ 2094'	12-68*	620'FNL & 580'FEL Sec 28
28-17	Pan Am Mammie L. Gray #5 Serial #128906	6-69	/-1790/ 1829'	6-69*	260'FNL & 615'FEL Sec 28
28-18	James L. Mason, Jr. Roger Simon Et Al #1 Serial #73227	12-58	/ /-3330[2] 3333'	.17-217, 750-850 :750-2850' 12-58	1998'FNL & 1372'FEL Sec 28
28-19	Cities Service Fee #1	3-58	/-1639/-2055	Storage	200'W & 200'S NE corner NW/4 NW/4 Sec 28 per agreement survey
28-20	Cities Service Fee #2	4-59	/-1613/-2056	Storage	506.5'W & 460'S NE corner NW/4 NW/4 Sec 28 per agreement survey
28-21	Cities Service Jaubert #3	5-57	/-1561/	Storage	300'E & 300'N SW corner SE/4 SW/4 Sec 21 per agreement survey
28-22	Cities Service Jaubert #1		·495/-1530/-2049	Storage	339'W & 300'N SE corner SE/4 SW/4 Sec 21 per agreement survey

[1] BB = Base of "B" Sand; TC = Top of Caprock; TS = Top of Salt [2] No Salt

* Temporarily Abandoned

TABLE A-2
EXPLORATION HOLES

Completion Date	Operator & Lease Name		BB / TC / TS[1] Total Depth	ugging Interv Plugging and Aban. Date	Location
28-23	Cities Service Jaubert #2	4-57	/-1574/	Storage	341'E & 300'N SW corner SW/4 SE/4 Sec 21 per agreement survey
28-24	Cities Service Fee #8	7-67	/ /-2056	Storage	590'W & 250'N SE corner SW/4 SE/4 Sec 21 per agreement survey
28-25	Cities Service Fee #6	11-69	/-1666/-2062	Storage	200'W & 300'N SE corner SW/4 SE/4 Sec 21 per agreement survey
28-26	Cities Service Fee #11	2-78		Storage	1230'FEL & 100'FNL Sec 28
28-27	Cities Service Jaubert #4	6-57		Storage	300'W & 300'N SE corner SW/4 SE/4 Sec 21 per agreement survey
28-28	RJ Coleman Ludger Duhon #1 Serial #68425	11-57	/ /-3410[2] 3451'	100-200' 950-1050' 3320-3390' 11-57	1145'FSL & 1220'FWL Sec 28
28-29	RJ Coleman VH Sudwischer #1 Serial #57177	6-54	-545/ /-3100[2] 3125' (sd sh)	100-200' 709-804' 3020-3120' 6-57	1855'N & 1389'W SE corner SW/4 Sec 28
28-30	RJ Coleman VH Sudwischer #2	6-55	-563/ / 3088'	100-200' 725-825' 2940-3040' 6-57	1855'N & 1389'W SE corner SW/4 Sec 28
28-31	RJ Coleman VH Sudwischer #4 Serial #65591	1-57	-537/ /-2970[2] 3030'	100-200' 750-850' 2850-2900'	1726'FSL & 632'FWL Sec 28

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt [2] No Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals: BB/ TC / TS[1]	Total Depth	Plugging and Aban. Date	Location
28-32	Freeport Sulfur Nathaniel Little #1 Serial #29533		/-1921/			670'N & 100'E center Sec 29
28-33	General American Oil Co. Porter Ellender #1 Serial #128012	4-69	/ /-5875[2]	5885'		660'S & 600'W NE corner SE/4 Sec 28
28-34	Michael T. Halbouty WH 2nd Can RA SUG-N-13 #2					700'FSL & 100'FEL Sec 28
28-35	Herbert McDonald Oil Co. William Reasoner #2 Serial #64388		-555/ /	3190'		158'N & 782'E center Sec 28
28-36	Harry Hunt Inc. Natalie Vincent Et Al #1 Serial #66402	3-56	-556/ /	3010'		158'N & 282'E center Sec 28
28-37	Sunshine Oil Johnie Benoit #1	4-29		2147' (salt)	4-29	66'W & 52'N SE corner SW/4 NW/4 Sec 28
28-38	Sunshine Oil Dupra Vincent #1	5-29	/ /-2054	2079' (salt)	5-29	50'N & 50'W SE corner SE/4 NW/4 Sec 28
28-39	Sutton Joint Acct. Edith Ellender #2 Serial #62190	8-56	/ /-3370[2]	3369'		1270'S & 200'W NE corner Sec 28
28-40	Sutton Joint Acct. Edith Ellender #3 Serial #68071	4-58	/ /-3520[2]	3515'		2210'S & 1395'W NE corner Sec 28
28-41	Sutton Joint Acct. Edith Ellender #4 Serial #68499	3-58	/ /-3300[2]			2481'S & 1755'W NE corner Sec 28

[1] **BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt**   [2] No Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals: BB / TC / TS[1] Total Depth	Plugging Intervals: Plugging and Aban. Date	Location
28-42	Sutton Joint Acct. Gulf Noble #1 Serial #61099	4-56	3415'		1370'S & 75'W NE corner Sec 28
28-43	Sutton Joint Acct. Gulf Noble #2 Serial #61664	7-56			1370'S & 225'W NE corner Sec 28
28-44	Sutton Joint Acct. Gulf Noble #3 Serial #63554	1-57	-605/ / 3470'		1550'S & 365'W NE corner Sec 28
28-45	H.E. Dalton Kaough #1 Serial #16964	11-35	3172' (oil sand)	11-35	275'N & 250'W SE corner NW/4 SW/4 Sec 28
28-46	Harry Hunt Inc. Natalie Vincent #2 Serial #69416	3-58	3306' (shale)		630'E & 100'S NW corner NW/4 SE/4 Sec 28
28-47	Stanley B. Rush I.V.Y. J. Ellender #1 Serial #63640	11-56	2970'	0-30', 200-360' 11-56	1270'FNL & 465'FEL Sec 28
28-48	Sailers Well Serv. Co. V.H. Sudwischer #6	7-57	3055'	11-68	1894'FSL & 1968'FWL Sec 28
28-49	RJ Coleman VH Sudwischer #3 Serial #64709	1-57	-563/ /-3250[2] 3283'	11-68	1996'FSL & 1203'FWL Sec 28
28-50	Guy Scroggins Dupra Vincent #1 Serial #71176	7-58	/-2034/ 2221'	8-58	75'N & 50'W SE corner NW/4 Sec 28
28-51	Southwest Enterprises C.W. Krumm #1 Serial #69389	1-58	-557/ /2230[2] 2264'	0-25', 55-155', 1850-1944' 8-59	2482'FNL & 2432'FEL Sec 28

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt [2] No Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals: BB / TC / TS[1] Total Depth	Plugging Intervals: Plugging and Aban. Date	Location
28-52	Southwest Enterprises CW Krumm #2 Serial #70269	7-58		NA	80'N & 125'E center Sec 28
28-53	Sutton Joint Acct. Edith Ellender #1 Serial #60614	4-56	/ /-3400[2] 3348'	0-30', 3268-3328', 12-71	1270'FNL & 50'FEL Sec 28
28-54	JG Sutton Co. D. Kaough Serial #21281	1-46	3060'	0-10', 100-150', 2958-3058' 3-51	460'N & 75'W SE corner NW/4 SW/4 Sec 28
28-55	Thos. W. Blake, Jr. Blake Oil Co.-Benoit 1 Serial #53342	11-54	-525/ / 2002'	0-750',1500-? 11-54	800'E & 100'N SW corner NW/4 Sec 28
28-56	Sutton Joint Acct. Nathaniel Little #1	8-36	1408'		415'FEL & 980'FNL Sec 28
28-57	Sutton Joint Acct. Nathaniel Little #3	1-54	1889'		90'FEL & 120'FNL Sec 28
28-58	Wentworth & BJ Vincent #1	1-58	-555/ / 2071'		259.3'FSL & 315'FWL SW/4 NE/4 Sec 28
28-59	Pan Am B. J. Vincent #2				415'FNL & 2120'FEL Sec 28
28-60CS	Sunshine Oil Benoit #1	4-29	/-1975/ 2147'		2450 FSL & 1100 FWL
28-61CS	Operator Unknown Lease Name Unknown		/ /-2088		2400 FSL & 1600 FWL
28-62CS	Operator Unknown Lease Name Unknown		/ /-2076		2500 FSL & 2300 FWL

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

[2] No Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals BB / TC / TS[1] Total Depth	Plugging and Aban. Date	Location
29-1	Brownie Drlg. Co. Inc. Floyd Little Et Al #1 Serial #120308	10-65	2413'	0-10, 2175-2375' 10-68	S/2 Sec 29, 461'FNL & 2751'FEL
29-2	Southwest Enterprises Vincent Et Al #2-B	9-58	-510/ / 2717'		100'FWL & 1325'FSL Sec 29
29-3	Ballard & Cordell Corp. Dugas Et Al #1	3-62	/ /-3100[2] 3117'		1550'N & 850'W SE corner Sec 29
29-4	RJ Coleman Benson-Vincent #2	5-55	2865' (shale)		2391'E & 1020'N SW corner Sec 29
29-5	RJ Coleman Benson-Vincent #1 Serial #54439	11-54	-554/ / 2976'		1059'FSL & 2450'FEL Sec 29
29-6	Superior Oil B. Vincent Et Al #B-2	1-54	2950'	0-25',850-950', 2802-2852' 3-54	750'N & 600'E SW corner Sec 29
29-7	RM Hutchins Jr Et Al Vincent Estate "A" #1	10-62	3010'		800'N & 550'E SW corner SE/4 SW/4 Sec 29
29-8	Superior Oil B. Vincent Et Al B#1	9-52	2950'	0-20',550-650', 2701-2801' 9-62	500'N & 200'E SW corner SW/4 Sec 29
29-9	Superior Oil Dorisse Kaough "D" 1	6-52	3893'	producing	500'N & 1120'E SW corner Sec 29
29-10	Ballard & Cordel Watts #1	12-62	2879'		160'N & 1380.1'W SE corner Sec 29

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

[2] No Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Intervals Plugging and Aban. Date	Location
29-11	RJ Coleman Jasper Little Et Al #1 Serial #69827	3-58	-498/-1810/ 1833'	100-200', 800-900' 3-58	2097'FNL & 829'FEL Sec 29
29-12	RD MacDonald Jr. BD Dugas #1 Serial #74240	3-59	-568/ / 3150'	0-10',175-275', 900-1000' 3-59	1321'FSL & 800'FEL Sec 29
29-13	Freeport Sulfur Archie Little #1 Serial #29372	4-44	/-1647/-2147 1777' (anhy)	4-44	300'FNL & 1800'FEL Sec 29
29-14	Freeport Sulfur William Little #1 Serial #29561	8-44	-490/ /-2500 2521'	8-44	315'S & 270'W of center Sec 29
29-15	Freeport Sulfur JM Vincent #1 Serial #29407	6-44	-635/-1863/-2085 2148' (salt)	6-44	160'S & 50'E SW corner SW/4 NW/4 Sec 29
29-16	Freeport Sulfur JM Vincent #4 Serial #29654	9-44	-485/-1870/-2068 2118' (salt)	9-44	85'N & 270'W center Sec 29
29-17	PJ Johnson L. Sanner #1 Serial #19402	2-37	1787'	2-37	1370'S & 2370'E NW corner Sec 29
29-18	Union Sulphur Coleman #1	4-27	1836'		950'FEL & 2075'FNL Sec 29
29-19	Independent Oil Co. L. Sanner #1	6-37	1775'	6-37	1352'FNL & 925'FWL Sec 29
29-2ocs	Operator Unknown Lease **Name** Unknown		/-1863/-2105		**2650 FSL & 1300 FWL**
29-21CS	Operator Unknown Lease name unknown		/-1995/-2099		200 FSL & 1100 FWL

[1] **BB = Base** of "B" Sand; **TC = Top** of **Cap** Rock; TS = **Top of Salt**

TABLE A-2
EXPLORATION HOLES

Base Map #	Op... e Name	Completion Date	BB / TC / TS[1] Total Depth	Plugging Interva Plugging and Aban. Date	Location
30-1	Superior Oil B. Vincent #6	9-39	/ /-8300[2] 7297'		330'N & 330'W SE corner NW/4 SW/4 Sec 30
30-2	Superior Oil B. Vincent #1	5-38	/ /-6900[2] 6913'		1320'N & 300'W SE corner SW/4 Sec 30
30-3	Superior Oil B. Vincent #2	7-38	/ /-6500[2] 6525'		1143'N & 477'W SE corner SW/4 Sec 30
30-4	Superior Oil R. Vincent #2	2-40	/ /-8200[2] 8265'		330'S & 330'W NE corner SW/4 SW/4 Sec 30
30-5	Dixon Mgr. R. Vincent #1	8-58	-600/ / 3986'		125'W & 240'S center Sec 30
30-6	Superior Oil B. Vincent #3	8-38	6632'		850'N & 200'W SE corner SW/4 Sec 30
30-7	Superior Oil B. Vincent #8	12-39	/ /-7664[2] 7664'		330'N & 330'W SE corner SW/4 Sec 30
30-8	RJ Coleman B. Vincent #1 Serial #67575	2-55	/ /-3450[2] 2983' (shale)		1370'FSL & 1270'FEL Sec 30
30-9	John H. McDonald D. Kaough #1 Serial #75089	6-59	4040'	-25',275-375', 750-850' 6-59	990'S & 820'E center Sec 30
30-10	Freeport Sulfur Gulf Refining Co. #1 Serial #29373	5-44	-510/-1771/-2104 2106'	5-44	900'FNL & 500'FEL Sec 30
30-11	Freeport Sulfur JM Vincent #2	6-44	2148' (salt)	6-44	720'FNL & 460'FEL Sec 30

1 BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt

2 No Salt

TABLE A-2
EXPLORATION HOLES

Base Map #	Operator & Lease Name	Completion Date	Plugging Intervals: BB / TC / TS[1] Total Depth	Plugging and Aban. Date	Location
30-12	RE Seiss JM Vincent #2 Serial #14388	4-32	2950' (gravel)	4-32	2395'S & 1355'W NE corner Sec 30
30-13	Seiss Vincent #1		/-1963/-2063 2111'		2520'FNL & 1275'FEL Sec 30
30-14	Seiss Vincent #1		2010'		2312'FNL & 1160'FEL Sec 30
30-15	Gulf D. Kaough #1		2131'		1275'FEL & 2285'FNL Sec 30
30-16	Amoco Gulf Land "A" R/C "C" #121 Serial #110305	9-65	/ /-5600 5718'		830'S & 1500'E of NW/C Sec 30
30-17	Amoco Gulf Land "A" R/C "C" #195	9-73	/-2120/-2250 2743'		847'FNL & 2402'FWL Sec 30
30-18CS	Operator Unknown Lease name unknown		/-2041/-2241[3]		1350 FNL & 2600 FEL
30-19CS	Operator unknown Lease name unknown		/ /-4684		1985 FNL & 2000 FWL
30-20CS	Operator unknown Lease name unknown		/ /-5130		1550 FNL & 1675 FWL
30-21CS	Operator unknown Lease name unknown		/ /-4654		1450 FNL & 1800 FWL
30-22CS	Operator unknown Lease name unknown		/ /-4263		750 FSL & 1550 FEL

[1] BB = Base of "B" Sand; TC = Top of Cap Rock; TS = Top of Salt
[3] Estimate

TABLE A-3

WATER WELLS IN THE VICINITY
OF THE WEST HACKBERRY SITE

Well No.	Date Drilled	Depth (ft)	Screened Interval (ft)	Yield (gpm) Specfic Capacity (gpm/ft d.d.)
CN 49	June 1944	2148	S-B	-em
CN 64	March 1957	506	461-505	---
CN 65	April 1957	235	215-235	m-v
CN 66	April 1957	506	423-503	S.C = 95
CN 69	Sept. 1925	480	399-479	S.C. = 60.2
CN 91*	August 1963	420	377-419	Yield = 50 gpm
CN 95	May 1964	512	502-512	Yield = 20 gpm

*Water had 100 ppm CH_4, pH 6.9

APPENDIX B

IMAGERY ANALYSIS

APPENDIX B

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APPENDIX B

IMAGERY ANALYSIS

Faults in the Gulf Coast are generally recognized as lineaments defined by tonal and topographic differences on remote sensing imagery[52,124]. Therefore, a variety of remote sensing imagery of the West Hackberry dome area was studied to identify lineaments. Photographic lineaments are defined for the purposes of this study as the visual manifestation of linear features consisting of tonal, topographic, and drainage alignments. Linear tonal patterns, which may represent structures in the Gulf Coast area, are termed Imagery Observed Tonal Anomalies (IOTA).

B.l TECHNIQUES

A variety of remote sensing imagery was utilized in this study, including LANDSAT satellite imagery, NASA high altitude color infrared photography, and three sets of conventional black and white aerial photography flown during the years 1933, 1955, and 1978. LANDSAT imagery was of limited usefulness in this study because of the extremely small scale. NASA high altitude photography proved to be the most useful in defining lineaments due to ability to highlight moisture differences.

The imagery was interpreted both in composite mosaics and in stereo pairs. Lineaments were transferred from mosaics of the three sets of aerial photographs and were plotted on a topographic map overlay at a scale of 1:24,000 to compare results from the various sets of photographs.

Lineaments detected by using a steroscope on individual photographs were marked on clear individual photograph overlays and were also plotted on the large overlay (1:24,000). For each black and white aerial photograph and color infrared photograph, a lineament analysis form (Figure B-l) was completed to document the basis for selection of each lineament.

The lineaments were color-coded on the overlay (1:24,000) to identify the set of aerial photographs from which they were identified, and each lineament was assigned a number. A total of 32 lineaments were identified and compiled from the remote sensing imagery.

B.2 LINEAMENT DOCUMENTATION

A map of observed lineaments was prepared on a base of 1:24,000 topographic coverage of the dome (Figure 4.5). On this map, each lineament is numbered, and the number of sensors on which it is detected is also indicated.

The results of the aerial photograph evaluation are tabulated in Table B-l. The explanations of column headings of Table B-l are as follows:

Lineament No. - The number assigned to each lineament.

Sensor - Many of the lineaments were detected on more than one sensor, so an X is placed in the column of each sensor type on which all or any portion of the lineament was observed.

1) 1933 black and white conventional aerial photographs (scale 1:25,000)

2) 1955 black and white conventional aerial photographs (scale 1:25,000)

3) 1978 black and white conventional aerial photographs (scale 1:39,063)

4) Color infrared NASA high altitude color infrared aerial photographs (scale 1:60,000)

Length - The length of the lineament as plotted on Figure 4.5.

Orientation - An approximate measure of the strike of the lineament is noted. Many of the lineaments have an arcuate or somewhat sinuous trace and do not lend themselves to a single bearing. Hence, the general trend of the lineament was measured, and in the case of an extremely variable or sinuous lineament, note was made of this variance.

Basis for Evaluation of Data - The following criteria were used to indicate the presence of lineaments on the remote sensing imagery evaluated in this study.

1) Alignment of drainage

An X is placed in this column if part or all of the lineament is indicated by linear drainage patterns.

2) Alignment of topography

An X is placed in this column if part or all of the lineament is indicated by lake shoreline alignment or linear patterns of old meanders or low areas.

3) Break-in-slope

An X is placed in this column if all or part of the lineament is indicated by a break-in-slope.

4) Change in vegetation tone

An X is placed in this column if all or part of the lineament is indicated by a tonal contrast of vegetation (IOTA) or an alignment of pimple mounds.

5) Change in vegetation type

An X is placed in this column if all or part of the lineament is indicated by alignment of a change in vegetation type.

Comments - This column is used to record the interpreter's additional comments and document any unusual aspects of the lineament.

B.3 CORRELATIONS

The lineament analysis was subsequently utilized in the surface geology analysis (Section 4.4). Most of the lineations observed on the remote sensing were coincident with anomalous areas on the sections and maps. Disturbed or irregular zones indicated on structure contour maps appear to relate directly to the lineaments identified in this study. The imagery analysis assisted directly in interpretation of the subsurface geology.

A comparison of the structure contour map on the base of the "B" sand (Figure 4.6) and lineaments over the dome (Figure 4.5) yielded the following observations of coincidence of lineaments and faulting associated with the West Hackberry dome:

- The general trend of the lineaments, northeasterly and northwesterly, agrees with the trend of the faulting in the "B" sand.

- Lineament 6 aligns with the major fault paralleling the northwest edge of the dome. The southerly portion of this fault dips about 55 degrees northwest, then becomes more vertical in the northerly part of the trace.

- Lineament 4 correlates with the southernmost radial fault that extends across the horst. This fault dips approximately 43 degrees southwest.

- Lineament 5 coincides with the north-trending fault on the western flank of the dome. The dip is near vertical. The northwest-trending fault on the eastern flank of the dome coincides with Lineament 20.

- The major northeast-trending fault on the southeast flank of the dome parallels the trend of Lineament 2. Lineament 1 agrees with the sense of displacement of the northernmost 4,500 feet of this fault; however, the dip of this fault would be 16 degrees, which does not fit with observed angles of dip associated with salt domes in the Gulf Coast. Some additional data or interpretation may be required for a "best fit" position.

- Lineaments 7, 8, 9, 10, 11, 12, 13, 14, 28, 30, and 31 may represent a fault system associated with a rim syncline on the northwest flank of the dome.

B.4 CONCLUSIONS

Lineaments observed over the dome fit patterns of faulting known to be associated with salt piercement structures and were useful in analyzing the surface and subsurface geology at West Hackberry dome. Most lineaments that were identified have been correlated with subsurface structures defined by well log data and could be directly interpreted as faults.

LINEAMENT ANALYSIS FORM LINEAMENT NO.___________

I. Image analyst_______________________________________Date____________________
Image Type____
Image No.__________________Image Date__________________Image Scale__________________
Township____________________Range__________________Section____________________

II. ORIENTATION: map measure__________, comments-__________________________________
LENGTH: map measure_____________, comments____
FORM: linear_________________, arcuatq____________________, sinuous__________________
comments____

III. NATURAL FEATURES DEFINING LINEAMF,NT

1. Veg. Type: contrast___________9 alignment___________, comments____________________
____
____

2. Veg. Tone: contrast__________, alignment___________, comments____________________
____
____

3. Topographic: linear valley(s)_______________, depression____________________________
break in slope_____________________, comments__________________________________
____
____
____

4. Spring(s)_______________________, comments__________________________________
____

5. Groundwater Barrier______________________________, comments____________________
____

6. Displacement______________, horizontal______________, vertical____________________
comments____
____
____

7. Other____
____
____
____
____

IV. PHOTOGEOLOGIC INTERFRETATION
____
____
____
____
____

V. PLACES TO FIELD CHECK
____
____
____
____
____
____

TABLE B-1

Tabulation of Characteristics
of Lineaments and Data Used in Imagery Analysis

	Sensors						asis r Evaluation of Data					
Lineament No	1933 B & W	1955 B & W	1978 B & 3	Color Infrared	Length (ft)	Orientation	Alignment of Drainage	Alignment of Topography	Break in Slope	Change in Vegetation Tone	Change in Vegetation Type	Comments
1	X	X	X	X	6400	N75E	X			X		Black Lake Bayou does not meander across lineament. Hill creates obvious break in linear trend.
2	X	X	X	X	15800	N45E	X			X		Alignment of gully is linear. Also defined by old meander channels.
3	X	X			19000	N85E				X		Vegetation tone difference especially evident in fields in southern portion of 1933 photo no. BOJ-5-81.
4		X	X	X	13200	N85W to N65W arie				X	X	Alignment of pimple mounds indicate lineament; linear meander patterns.
5		X	X	X	11800	N5E		X		X		Linear break in land/water interface.
6	X	X	X	X	16600	N50E		X		X		Alignment of lake shore; variation in tone of pimple mounds; linear break in land/water interface.
7	X	X	X	X	15000	N50E to N80E ries	X	X		X		Alignment of wells in oil field follows lineament seen in 1933 photos. Break in land/water interface.
8	X				7400	N801				X		
9	X				5400	N100				X		
10	X	X			7600	N30'	X		X	X		S 2383 feet: break-in-slope; Small linear lake inlet.

TABLE B-l

Tabulation of Characteristics
of Lineaments and Lata Used in Imagery Analysis

	Sensors						Basis or Evaluation o Data					
Lineament No.	1933 B & W	1955 B & W	1978 B & W	Color Infrared	Length (ft)	Orientation	Alignment of Drainage	Alignment of Topography	Break in Slope	Change in Vegetation Tone	Change in Vegetation Type	Comments
11	X	X			4500	N602		X		X		Vegetation tone aligns with N. Black Lake shoreline.
12	X				1100	N10W				X		
13	X				7500	N20W				X		
14	X				6700	N70E				X		
15	X				1600	N2W				X		
16			X	X	17300	N60E				X		
17		X	X	X	5800	N35W		X		X		trip of land emphasizes southern art of lineament (color infrared)
18	X	X	X	X	7300	N80W		X		X		inear break of land/water nterface (1978)
19	X	X	X		16800	N85W to N50W varie	X	X		X		onal contrast emphasized by lignment of low area; lignment of meander channel scar
20	X	X	X	X	1000	N30W	X	X		X		ounded on N side by rise; linear ully and meander alignment; tonal ontrast across Hackberry school ield (1978)

TABLE B-l

Tabulation of Characteristics
of Lineaments and Data Used in Imagery Analysis

	Sensors						Basis for Evaluation of Data					
Lineament No.	1933 B & W	1955 B & W	1978 B & W	Color Infrared	Length (ft)	Orientation	Alignment of Drainage	Alignment of Topography	Break in Slope	Change in Vegetation Tone	Change in Vegetation Type	Comments
21			X	X	4000	N40W	X			X	X	Alignment of meander belt.
22		X	X	X	4000	N55W	X			X		E 6000 feet: presence of pimple mounds north of Lineament.
23		X	X	X	730(	N40E	X			X	X	Lineament marked by meander belt alignment.
24			X		850(	N20E				X	X	
25	X	X			100(	N35W to N50W tries				X		
26		X			350c	N10W						2708 feet indicated by contrast of density of brush; 3125 feet rise on east side of lineament.
27	X	X			600C	N62E			X	X	X	
28	X	X			1300	N40E				X		
29	X				860(	N30W				X		
30	X				930(	N50E				X		

TABLE B-l

Tabulation of Characteristics
of Lineaments and Data Used in Imagery Analysis

	Sensors						asis r Evaluation of Data					
	1933 B & 3	1955 B & 3	1978 B & W	Color Infrared	Length (ft)	Orientation	Alignment of Drainage	Alignment of Topography	Break in Slope	Change in Vegetation Tone	Change in Vegetation Type	Comments
	X				540(	N651				X		
				X	780(	N301				X		

APPENDIX C

LIST OF CONTACTS

STATE AND FEDERAL ORGANIZATIONS

ORGANIZATION	LOCATION	PERSON(S) CONTACTED
Louisiana Department of Conservation	Lake Charles, Louisiana	Frank Perkins
Louisiana Department of Public Safety Explosive Control Section	Baton Rouge, Louisiana	Lt. W. Poe
Louisiana Geological Survey	Baton Rouge, Louisiana	Diana Getaris Virginia Van Sickle
Louisiana State University Division of Engineering Research	Baton Rouge, Louisiana	Dr. Jack Hill
National Aeronautics and Science Administration EROS Data Center	Sioux Falls, South Dakota	Brenda Redmond
National Oceanographic and Atmospheric Administration	Asheville, North Carolina	Fred Doring
National Ocean Survey Datums and Information Branch	Rockdale, Maryland	Ray Smith
National Space Technology Laboratories	NSTL Station, Massachusetts	Dave DeBlanc Nancy Hagin
U.S. Army Corps of Engineers	New Orleans, Louisiana	Harris Blanchard Bill Garrett Gary Gilino Roni Ventola
U.S Army Corps of Engineers Flood Plain Management-Report Section	New Orleans, Louisiana	Dave Lienknecht Jay Combe R. J. Kliebert
U.S. Army Corps of Engineers Lock Operations Section	New Orleans, Louisiana	Gregory Breerwood
U.S. Army Corps of Engineers Navigation Branch	New Orleans, Louisiana	R. J. Hardy

STATE AND FEDERAL ORGANIZATIONS
(Continued)

ORGANIZATION	LOCATION	PERSON(S) CONTACTED
U.S. Department of Commerce National Geodetic Survey	Rockville, Maryland	Mike Day, Horizontal Network Mr. Hoyle Ed McKay, Lambert Grid Captain Phillips John Till, Vertical Network
U.S. Department of Energy	New Orleans, Louisiana	Don Whittington
U.S. Department of Energy	West Hackberry SPR Site	Allen Fruge
U.S. Department of Interior Bureau of Mines	Denver, Colorado	Bob Speirer
U.S. Geological Survey	Baton Rouge, Louisiana	George Arcemont Raymond Sloss
U.S. Geological Survey	Denver, Colorado	Wilfred Hasbrouk
U.S. Geological Survey Public Inquiries Office	Dallas, Texas	Jay Donnelly
U.S. Geological Survey Division of Water Resources	Baton Rouge, Louisiana	Dale Nyman

PRIVATE ORGANIZATIONS

ORGANIZATION	LOCATION	PERSON(S) CONTACTED
Ace Geophysics	Houston, Texas	Bud Coyler
Amoco Production Co.	Houston, Texas	Ed Clements Dave Daniel, Computer Services Bob Miles, Project Geologist
Amoco Production Co.	New Orleans, Louisiana	J. Bohling Joe Burns Dave Gillian, Onshore Production Mgr. Ed Williamson, District Geologist Gulf Coast
Associated Industries	Houston, Texas	Lou Divita
Austin Exploration	Houston, Texas	T. Austin
Baird Petrophysical Group	Houston, Texas	T. Toschlog
Cambe Geological Services	Houston, Texas	Dorothy Harbison
Cities Service Oil Co.	Houston, Texas	Norman Jenkins, Project Geologist
Dravo Utility Constructors, Inc. (DUC I)	Bryan Mound, Texas West Hackberry SPR Site New Orleans, Louisiana	Maurice Graber Steve Lowry Jerry Thompson
EDCON	Denver, Colorado	A. Herring
Exploration Techniques, Inc.	Houston, Texas	W. Pustejovsky
Fairfield Industries	Houston, Texas	Niel Moore

PRIVATE ORGANIZATIONS
(Continued)

ORGANIZATION	LOCATION	PERSON(S) CONTACTED
Gasch and Associates	Sacramento, California	J. Gasch
Gaylord & Stickle Co. & Assoc., Inc.	Houston, Texas	Map Services
GeoGravity Inc.	Houston, Texas	
Geophysical Data Banks of Texas	Houston, Texas	Denise Ahmad
Geo Source	Houston, Texas	John Coskey
Geo Space	Houston, Texas	Geophysical Operations
Gulf Coast Geodata Corp.	Houston, Texas	John F. Asma
Input-Output	Houston, Texas	Computer Operations
Jacobs D'Appolonia	Houston, Texas	Ricky Canningham
Louis Records	Lafayette, Louisiana	Wanda Hopkins
Macobar	Cameron, Louisiana	Geophysical Operations
Mark Roberts	Houston, Texas	Barbara Grey
Meyer Group	Sulphur, Louisiana	Al Hansen Steve Hebert
Mobil Oil Corporation	Denver, Colorado	Laura Fox, Petroleum Geologist
Northern Ohio Geological Society	Case Western Reserve University, Ohio	Dr. Hail, Chairman, Department of Earth Sciences

PRIVATE ORGANIZATIONS
(Continued)

ORGANIZATION	LOCATION	PERSON(S) CONTACTED
Olin Corporation	Lake Charles, Louisiana	R. B. Colley, Mgr. Brining Operations
Parsons-Gilbane	New Orleans, Louisiana	N. L. Rushing
Petroleum Information	Houston, Texas	
Prokop Exploration, Inc.	Houston, Texas	Ben Prokop
Pyburn & Odom	Baton Rouge, Louisiana	Roy Odom Kevin Wegener
Schlumberger Logging Services	Lake Charles, Louisiana	Logging Services
Seismic Equipment Exchange	Lafayette, Louisiana	Clay Mires
Sigma Geophysical	Houston, Texas	Ray Griffith
Southwest Laboratories	Beaumont, Texas	George Cozart
STM Corporation	Houston, Texas	Roger Willhite
Texas Brine	West Hackberry SPR Site	Frank Whelpy
Tidelands Geophysical	Houston, Texas	G. Killough
Tobin Research, Inc.	San Antonio, Texas	Joe Vega
University of Missouri at Columbia	Columbia, Missouri	Alden B. Carpenter
Western Geophysical Co. of America	Houston, Texas	John Farr

PRIVATE ORGANIZATIONS
(Continued)

ORGANIZATION	LOCATION	PERSON(S) CONTACTED
Whitaker & Webb	Lake Charles, Louisiana	Philip Whitaker
Zingery Map Company, Inc.	Houston, Texas	

APPENDIX D

STRATEGIC PETROLEUM RESERVE
CORE LOGGING PROGRAM

APPENDIX D

STRATEGIC PETROLEUM RESERVE
CORE LOGGING PROGRAM

INTRODUCTION

This appendix outlines the procedure used for logging core from the West Hackberry, Bryan Mound, and Bayou Choctaw Strategic Petroleum Reserve Sites. This procedure provided a permanent, consistent, and accurate core log of the existing core of the overburden, cap rock, and salt collected at the three sites mentioned above.

A total of 7,390 feet (467 boxes) of disposal well core and 5,590 feet (624 boxes) of salt core were logged (Table D-l). The actual logging required:

1) Opening the boxes and removing the core from the plastic wrap.

2) Photographing the core in groups of three to seven sections and narrating physical properties on core logs (Figure D-l), including description of color, grain size, mineralogy, and structure.

3) Rewrapping the core, replacing the core in the boxes, and sealing. The boxes were then replaced in order on pallets.

The original log was checked and initialed by the geologist-in-charge at the warehouse site. The core logs were checked against the photographs, and a final check was performed by the Project Geologist after the photographs and logs were bound. Four sets of logs and photographs were produced and sent to Sandia National Laboratories.

TABLE D-1

LIST OF CAVERN HOLES AND BRINE DISPOSAL WELLS
INCLUDED IN CORE LOGGING PROGRAM

WEST HACKBERRY

DW 1A (Also phown as BD 1A)
RE 6C
RE 7A (Also shown as SPR 7A)
RE 7B
RE 8A
RE 9A (Also shown as SER 9A)

BAYOU CHOCTAW

DW2
DW 6
DW 12 (Also shown as BD 12)
CH 1
CH 2
RE 19A

BRYAN MOUND

104 A
104 c
106 A (Drill #107 A)
106 B (Drill #107 B)
106 C (Drill #107 C)
107 A (Drill #108 C)
107 B (Drill #108 B)
107 c (Drill #lot? A)
108 A (Drill #106 C)
108 B (Drill #106 B)
108 c (Drill #106 A)
109 A
109 B
109 c
110 A
110 B
110 c
DWl
DW 1A
DW2
DW 3A (Also shown as DW 3)
RE IA
RE 5A

FIGURE D-1

SHEET __ OF __

PROJECT: SPR Core Logging

CLIENT: SANDIA LABORATORIES

SITE:

BORING NO. ________

FILE NO. ________

DATE ________

ELEVATION: ________

LOGGED BY: ________

DEPTH (feet)	DESCRIPTION	REMARKS

WOODWARD—CLYDE CONSULTANTS

APPENDIX E

SPECIAL STUDIES
SURVEYING

APPENDIX E

SPECIAL STUDIES
SURVEYING

E.1 SURVEY SYSTEMS

At the outset of this study, four separate survey systems were identified for the site vicinity. The surveys included the U.S. Government Survey (section lines), Agreement Survey (second set of section lines), Lambert coordinates, and site coordinates. Most of the site facilities were related to site coordinates, although the site boundaries were identified by Lambert coordinates, On the other hand, most wells and test holes were located by the U.S. Government or Agreement Surveys. Because it was essentially impossible to relate one survey to another, and because personnel of Sandia National Laboratories had also been confronted with the same problem in their attempts ta identify well locations in the field, this contract was expanded so that Woodward-Clyde Consultants could conduct field survey investigations in an attempt to integrate the various surveys.

Woodward-Clyde contracted with the Meyer Group, Sulphur, Louisiana, to establish Lambert coordinates for existing wells and abandoned wells in and near the West Hackberry SPR facility and to identify the relationship of the Government Survey-Agreement Survey. The initial concern that originated the survey was the abandoned well located just east of proposed well Pad 101 (A.M. Barbe No. 1). Because this well was very close to a projected cavern hole, it was important to identify definitely the well so as to establish its plugging and abandonment record. This well was believed to have been located by the Agreement Survey, although most of the other wells at the site were located by the U.S. Government survey lines.

By establishing the locations of the above wells relative to one another and by knowing which survey was used to locate the wells with respect to the section lines (i.e., section lines determined by the U.S. Government and by John F. Parsons [the Agreement Survey]), it would be possible to work backwards and locate the relative positions of the two surveys. Also, by tying the wells to the Lambert coordinates, the wells presumably could all be related to plant facilities. The question relative to the Government Survey and the Agreement Survey was qui,ckly resolved; however, problems developed relative to the Lambert and site coordinate systems.

The Lambert coordinates were to be surveyed in from the "Hebert marker" (as were the site boundary coordinates) located some 2 miles south of the site. Prior to surveying, a visit to the Hebert marker established that the marker had been disturbed. It had been dug up (probably in search of the subsurface marker) and was lying in a hole. Inspection of the reference markers indicated that one of them had also been disturbed. Because of the disturbance of the Hebert marker, an accurate survey would require that coordinates be established from a different marker. Mr. Hansen of the Meyer Group indicated that the next closest available marker was located north of the facility at Ellender Bridge, some 11 miles from the facility. This information was confirmed through the National Geodetic Survey in Washington, D.C. Due to the increased time and cost of surveying with first-order accuracy, wells were related to the site coordinate system with the intent to convert those coordinates to Lambert using the equation on facility and construction Drawing No. C2l-101. The site coordinate system was then related to the Government survey lines with the aid of other site drawings.

Calculations were made to convert the locations of the wells to Lambert coordinates. An analysis of the rotation angle and/or the zero point in the equation on Drawing No. C21-101 revealed it to be in error. A check with the NGS in Washington, D.C., confirmed this fact. The NGS stated that the angle between the south zone Lambert grid system and a line oriented true north in the vicinity of the site should be N l02'5" W. It follows then that the site grid might not be oriented true north.

From discussions with other contractors at the site, the property lines (in Lambert coordinates) were found to have been brought in from the Hebert marker, and the marker appeared to be in an undisturbed state at the time the survey was conducted. Initially then, the coordinates for the bench marks of the property line were assumed correct.

The Meyer Group was again contracted to determine the orientation of the site grid and to relate the site grid to the Lambert grid, using the property line bench marks. The site grid was found to have an orientation of N OO44'10.8" E and the resultant angle between the Lambert grid and the site grid is l"46'15.8", differing from OO33'32" as it appears in the equation.

The new rotation angle was substituted into the equation, as were values of site coordinates and Lambert coordinates of a known point at the facility, to solve for the Lambert coordinate of the (0,0) point of the site grid. (The values of the [O,O] point are the constants that appear in the conversion equation.)

This calculation indicated that the (0,0) point in the equation was also in error. The calculation was repeated with another known point, and a third value for the (0,0) point was derived. It was hoped that two of the values would have agreed to within 1 foot. However, the errors were on the order of 40 feet. Consequently, the equation was abandoned.

It is apparent that, if the Lambert coordinate system is to be used at the site, the Lambert system should be surveyed in from the marker at Ellender Bridge. Also, if the site property boundaries are required to be "exact," they should also be adjusted by a new survey.

E.2 SUMMARY

The orientation of the various coordinate systems are as follows: both the U.S. Government and Agreement Surveys are oriented true north, i.e., N 0"OIO" E. The relative positions of the two surveys are shown on Figure 4.4. The orientations of the site coordinate system and the Lambert coordinate system are N 0"44110.8n E and N lO2'5" W, respectively. The resultant angle between the two is 1°46'15.8". At this time, no equation exists for converting from the site system to the Lambert system. One of the recommendations for Phase II work is to establish a geodetic network in the vicinity of the site to monitor subsidence. If horizontal control is established at the same time, it could be used to locate surface facili-. ties and property lines on a common base.

SECTION III

SALT PROPERTIES FOR WEST HACKBERRY DOME

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ABSTRACT

This section evaluates the properties of salt from the West Hackberry salt dome. The evaluation includes review of core, borehole logs and drilling reports to determine typical material properties and define anomalies. The typical quasi-static and creep properties of the salt are consistent with published values for salt from many worldwide locations. The typical impurities in this dome are anhydrite-halite layers with near vertical dip. Small quantities of anhydrite are also dispersed within the salt grains. The salt dome is suitable for the long-term storage for petroleum in caverns which can be constructed using normal leaching techniques.

Acknowledgment

The subsections with references indicated after the titles contain-direct excerpts and paraphrases from the references as well as statements that are not in the reference. Therefore, the authors of the references receive credit for preparation of a significant portion of this section.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND CONVENTIONS

$\sigma_1, \sigma_2, \sigma_3$	True principal stresses (force)/(current area) - compression positive
$\varepsilon_1, \varepsilon_2, \varepsilon_3$	Engineering strains (change of length)/(original length - contraction positive)
elt e2' e3	Natural or logarithmic strains (change in length)/(current length)
$y = e_1 - e3$	Shear strain
$e = e_1 + e2 + e_3$	Volumetric strain
e_X	Strain parallel to cylinder axis (axial strain)
6	Displacement
$(0, - c3)u$	Ultimate or maximum principal stress difference
k,) uI (e,),, e_U	Natural strain values corresponding to $(5 - \sigma_3)_u$
Aell Ae, be3	Finite stress and strain increments
ES	Secant modulus
E, vr P	Elastic constants (Young's modulus, Poisson's ratio, and shear modulus)

The bulk of the data is expressed in English units, consistent with SPR project requests.

SUMMARY

We determined material properties of West Hackberry dome salt from analyses of cores and from review of the geophysical borehole logs and well histories of Wells 6C and 8A. Analyses have begun for the zone where expansion caverns are to be leached. These data are preliminary and will be updated in a replacement for this section.

Quasi-static and creep tests were used to determine the mechanical properties (Tables l-6). Typical quasi-static results are shown in Figures 1 and 2.

Mineralogical values were obtained from X-ray diffraction tests on solid material, from chemical analysis of brines, and from microscopic study of solid sections (Tables 7 and 8). The quantity of insolubles, which are primarily anhydrite, was from 2% to 4% by weight in the core samples. The core samples do not represent anomalous zones but are probably typical of "clean" salt.

INTRODUCTION

One task of the geotechnical support program for the SPR system was to determine the material properties required to support cavern analyses. On November 21, 1979, SPRPMO requested Sandia to conduct a technical support program for early cavern leaching at Bryan Mound. As a result of this additional program, we redefined the material properties work to include a study of the mineralogy in the zone to be leached. We divided the materials work into four tasks: (1) definition of structural properties, (2) definition of sample mineralogy, (3) interpretation of geophysical logs, and (4) correlation of this information with data from other locations.

The task of defining the salt's structural properties included quasi-static and creep tests of selected 4-inch core. Sample mineralogy was determined by density evaluation, X-ray diffraction, chemical analysis, and background radiation tests of the 4-inch core, the drill cuttings, and the sidewall samples. Interpreting the geophysical logs involved primarily identification and location of anomalies. The task of correlation involved comparing data from West Hackberry with data from Bryan Mound dome salt, Waste Isolation Pilot Plant (WIPP) bedded salt, and data found in the literature.

The information presented in this section was generated during the short-term integration and engineering study program.[a] Because analysis of data from materials and borehole logs from the expansion caverns was not completed in time for this report, a replacement section will be issued (probably in mid-1981).

STRUCTURAL PROPERTIES'

This section describes the structural testing of core sampies, including quasi-static and creep tests.

Experimental conditions for ten structural tests are listed in Table 1. The test I.D. in the first column of Table 1 identifies all pertinent experimental parameters in the following format:

nominal specimen diameter (in inches), type of test*/
drill hole number-depth (in feet)/
confining pressure, 3 (ksi)/
test temperature in OC

Example: 4Q/6C-2206/O/22

The experimental condition selection was motivated by the need to (1) obtain data that can be compared directly with published results for rock salt from other locations, (2) evaluate the influence of temperature and confining pressure on the strength, ductility, and creep properties of West Hackberry material, and (3) ascertain differences in rock-salt responses between triaxial compression and triaxial extension.

EXPERIMENTAL RESULTS

QUASI-STATIC TESTS

The quasi-static data obtained are presented in Figures 1 and 2 through the use of conventional graphs of principal stress difference versus shear strain and volumetric strain. If we denote compressive strains as positive, the natural strains are obtained from measured dimensional changes and engineering strains as

el = -ln(l - 1~~1)

$e3 - \ln(l + |\varepsilon_3|)$

*Q, QE, C, or CE. Q and QE denote quasi-static triaxial compression and extension tests, respectively. C and CE refer to creep tests in triaxial compression and extension.

$$\gamma = e_1 - e_3$$
$$e = e_1 + e_2 + e_3$$

and e and γ are volumetric and shear strains, respectively.

Figure 1 compares the unconfined behavior of West Hackberry material at 22O and 60°C. The steps in the two stress-strain curves are results of the incremental deviatoric loading procedure. In subsequent plots, stepped stress-strain curves are sometimes approximated by smooth curves drawn through the end points of each step. Note that plots of principal stress difference versus shear strain and volumetric strain are the most appropriate representations to compare the results of triaxial compression and triaxial extension tests.

Supplementary data are provided in Tables 2 and 3. Table 2 lists the unconfined strengths and the associated ultimate strains. Table 2, Column 3, also contains the maximum stresses below the ultimate stresses that were reached at elevated values of σ_3. Note that the ultimate stresses were not reached at σ_3 = 2000 psi (13.8 MPa) and greatest compression strains $e_1 \leq$ 25.4% because the deviator stresses were still increasing when these experiments were terminated. However, observations of dilatancy* imply that fracture would have developed if the experiments had continued.

In view of the ductile nature of rock salt, the nonzero volumetric strain values that were monitored in triaxial compression and extension must be considered suspect in principle. To minimize uncertainty about the validity of these results, volumetric strains determined from records of axial and radial sample deformation were compared with volumetric strain estimates based on measurements of the final sample dimensions

*Dilatancy denotes increases in rock volume relative to purely elastic volume changes with changes in mean stress.

after testing. The latter values were entered in the last column of Table 2. They constitute relatively crude estimates because of local grain bulging. Except for Sample 6C-2223, the trend of the data in Columns 7 and 8 is consistent, although the quantitative agreement is poor.

Table 3 contains the values of secant moduli and principal strain ratios that describe shear response of West Hackberry salt upon first laboratory loading. Such values are often used to evaluate the behavior of rock salt from different sites; they also indicate the nonelastic nature of this material. The elastic properties of West Hackberry salt were established in rapid unloading tests at stresses below -60% of the previously attained peak stress when time-dependent deformation becomes subordinate.

CREEP EXPERIMENTS

The results of the four creep experiments are summarized in Tables 4 and 5 and in Figures 3 and 4. The unintentional variations in the initial loading rates (Columns 6 of Table 4) were caused primarily by restrictions in the flow rate through hydraulic lines and in the output capacity of one of the pressure sources. In spite of these restrictions, the initial loading rates were 14 to 94 times greater than the mean loading rate in all quasi-static tests. Nevertheless, the ratios of the data in Columns 2 and 6 in Table 4 (i.e., the stress differences divided by the initial loading strains that are equal to the secant moduli E_s) still fall into the relatively low range $4.4 \times 10^5 \geq E$ (psi) $\geq 2.3 \times 10^6$ (3 to 16.1 GPa) and are well below the intrinsic elastic modulus $E \sim 5.6 \times 10^6$ (39 GPa) (Table 3).

Figures 3 and 4 are plots of the measured shear strains and volumetric strains versus time. The cusp in the creep curve for Sample 6C-2201 (Figure 3) is caused by a gradual, 190-psi (1.3-MPa) stress drop between the 15th and 70th hour of testing when the stress was updated. This stress drop was caused by a considerable change in specimen area at constant applied force. Again, the observed volumetric strains are suspect, but no measurement errors could be identified. Increased dilatancy with an increase in temperature in the compression test in Figure 4 is unexpected. However, this dilatancy was associated with greater shear strains than those developed at 22°C. It may also be that the differences between results at ambient and elevated temperature are caused by compositional and textural variations between samples. The indicated compaction in Figure 4 for extension tests was computed independently by means of both indirect and direct measurements of radial specimen deformations.

DISCUSSION

The quasi-static data for West Hackberry salt are typical for rock salt from other sources. The salt behaves nonelastically even at low deviator stress, as indicated by the small secant moduli ES < 2.1 x 10^6 psi (14.6 GPa) in Table 3 compared with a Young's modulus of E = 5.6 x 10^6 psi (39 GPa). Pressure has a strong effect on the ultimate stresses and strains over the range of confining pressures applied here, 0 to 2000 psi (13.8 MPa). However, based on published data, the influence of pressure is bound to be greatest at a3 2 1500 psi (10.3 MPa) and decreases steadily as a3 is raised. For this reason, it was expected that the shear strains of West Hackberry samples would agree closely in triaxial compression and extension. In spite of the agreement in shear behavior, systematic differences remained in the volumetric strain response. If these results prove correct as indicated by cross-checks of all measurements, then the observed variations in volumetric strain response suggest persistent differences in strength between triaxial compression and extension even at relatively high a3. To test this point, additional experiments should be carried out to macroscopic fracture at several confining pressures up to a maximum of at least 13.8 MPa.

The temperature rise from 22o to 60°C produced only a minor change in the uniaxial compressive strength (Figure 1). The same 38OC change in temperature resulted in an almost twofold increase in the shear flow at elevated confining pressure (Figure 1). The exact value of this increase is probably a function of the imposed rate of loading. It is nevertheless confirmed that temperature must be considered in the choice of rock salt properties for design calculations.

Creep experiments at a = 2000 psi (13.8 MPa) produced similar results in several respects. Nearly identical behavior was monitored both at ambient and elevated temperatures (Figure 3). Nevertheless, the volumetric strain behavior (Figure 4) was systematically different in the two types of tests. This trend in the volumetric strains suggests a preferential nucleation and alignment of microcracks that has been verified in more recent tests on rock salt from another dome. Therefore, if creep rupture occurred, it probably would be different in compression from what it is in extension.

One objective of this study was to determine the comparative behavior of rock salt from West Hackberry, Jefferson Island, and the Wellington formation at Lyons. The latter comparison automatically raises the added question whether the properties of dome salt differ from those of bedded salt because of differences in tectonic histories. Available ambient temperature data from all three sites are summarized in Table 6. Several observations are readily apparent. The variation of the ultimate stresses, ultimate strains, and secant moduli upon first laboratory loading in Table 6 are well within the typical data scatter for large suites of tests on rock salt from any location. Agreement of data is particularly good considering that the results were obtained in different laboratories and on specimens of different sizes. The only apparent discrepancy exists in the magnitude of the intrinsic elastic constants (Column 6, Table 6). The most likely reason is a difference in measurement techniques and experimental resolution. However, it is emphasized that the high value of Young's modulus reported here for the West Hackberry core agrees perfectly with values of the Young's moduli that were computed from rock salt densities and from measured dilatational and shear-wave velocities. The elastic constants in Table 6 also agree with those obtained for rock salt from other locations.

SUMMARY AND CONCLUSIONS

Six quasi-static and four creep experiments on West Hackberry rock salt were described. All quasi-static test results, ultimate stresses and strains, elastic constants, and secant moduli during first laboratory loading were quite similar to data for rock salt from three other sources. Pressure effects are significant at low confining pressure. However, at σ_3 = 2000 psi (13.8 MPa) this effect was largely suppressed so that the shear behavior of West Hackberry salt was almost identical in triaxial compression and extension. On the other hand, systematic differences in the volumetric strains indicate that the ultimate stresses and strains might-differ in the two cases if such tests are continued to fracture. A small change in temperature from 22 to 60°C produced substantial changes in the shear flow of the West Hackberry core.

Creep tests in triaxial compression and extension were analyzed in terms of both the combined primary/secondary creep model and a purely transient formulation applied in earlier West Hackberry analyses. Both models described the experimental data well for the duration of the present tests ($t \leq 475$ hours). However, the combined primary/secondary interpretation was favored because it is consistent with known flow mechanisms in halite.

Almost identical shear creep data and systematically varying volumetric creep results in compression and extension suggest that pressure does not influence the flow of salt at σ_3 = 2000 psi (13.8 MPa) but that it might alter the development of creep rupture. Temperature had a very pronounced influence much like that in quasi-static tests. The comparison of creep data at 22° to 60°C implies an activation energy of Q = 11.4 kcal/mole (47.8 kJ/mole) for secondary creep, and U = 5.6 kcal/mole (23.4 kJ/mole) if creep is attributed solely to transient creep. If the temperature effect in the transient creep formulation is related to a power function of temperature, T^s, then s = 9.32.

Neglecting early time data, the results for West Hackberry salt compare well with creep data from the Jefferson Island dome and for bedded salt from the Wellington formation at Lyons, Kansas, and from the Salado formation of Southeastern New Mexico.

CHEMISTRY AND MINERALOGY[10]

Only three West Hackberry samples were analyzed during the time of this report. They were core segments labeled WH-6C-2208, WH-6C-2241/3 and WH-6C-2208 (same label as the first sample). These three samples were assigned laboratory identification numbers SPR-1, SPR-2, and SPR-3, respectively. Descriptions of the samples as received are given in Table 7.

Part of each sample was analyzed by X-ray diffraction to determine the major minerals present. In all cases halite (NaCl) was the major mineral. A small amount of anhydrite was also detected in each sample.

About loo-gram aliquots of each of the three samples were accurately weighed, dissolved in deionized water, and filtered to collect insoluble residue. The brine solutions produced were diluted to 500 millilitres for chemical analysis. See Reference 11 for additional details.

Results of the chemical analyses are given in Tables 8 and 9. The insoluble material in all three samples was identified as anhydrite ($CaSO_4$) by X-ray diffraction. The weight percentages of insoluble material are a function of dissolution conditions and should be used with caution. (See Reference 11 for a discussion of the effects of NaCl concentration and temperature on the solubility of anhydrite.)

Table 9 shows the data for the water-soluble fractions of the cores recalculated on a molar basis. The molar amount of Ca^{++} very nearly equals the molar amount of SO: in all three cases. This is strong evidence that all Ca^{++} and $SO_4^{=}$ in the solutions are the result of partial dissolution of the anhydrite from the samples. The column in Table 8 labeled Total $CaSO_4$ is the sum of the "Ca^{++}", "$SO_4^{=}$" and "Insoluble" columns of the table and should represent the total anhydrite contents of the original core samples.

Note also in Table 9 that the molar amounts of Na and Cl^- are about equal, consistent with both resulting from dissolving halite (NaCl). The K^+ contents of the samples are negligible compared to Na^+. The small amounts of K^+ are probably present as K^+ replacing Na^+ in the halite, but the presence of a very few, very small grains of sylvite (KCl) cannot be ruled out.

Other elements analyzed for in these samples are shown in Table 8. Bromine was detected in SPR-2 and SPR-3, but at too low a level for accurate calculation of concentrations. All other species in Table 8 were not detected above background.

All three samples were 94% or more halite (NaCl), with anhydrite ($CaSO_4$) the remaining material. No other phases were detected. Solutions prepared from the cores contained equivalent amounts of Na^+ and Cl^- and equivalent amounts of Ca++ and so;. These were the result of dissolving halite and anhydrite, respectively. Only anhydrite was detected in the insoluble residue. The fraction of the anhydrite in the sample that dissolved was a function of solution conditions--time, temperature, amount of stirring, and concentration of other ions in solution (especially Na^+ and Cl-). The total $CaSO_4$ column in Table 8'is the parameter most representative of the anhydrite contents of the original samples.

The total anhydrite ($CaSO_4$) contents of the three samples vary from -2.8 to 5.1 weight percent. The maximum variation is between SPR-1 and SPR-3, which came from the same l-foot core section. This is some indication of the variability in compositions that can occur over even short distances. Larger variations in other samples cannot be ruled out.

The anhydrite-rich sample SPR-3 contained visibly dark veins (Table 71, while SPR-1 did not. In the Bryan Mound samples I dark veins were found to be anhydrite-rich (Bild, 1980).[11] These West Hackberry results indicate dark veins in West Hackberry samples are also anhydrite-rich.

GEOPHYSICAL LOG REVIEW

Review of the available well histories from Louis Records & Associates, Inc. and the cavern certification documents did not provide significant geophysical log information on the salt in the area to be leached.

Some logs taken before and during the recertification program for Cavern 6 provided some information for depths between 2600 and 3270 feet. These logs did not indicate any conditions that would create major problems in cavern development.

As logs become available from drilling of the Expansion Caverns 101 through 116, they will be reviewed for problem areas. The results of the log and well history reviews will be published with the laboratory test results.

REFERENCES

1. Systems Integration and Engineering Support Study for the Strategic Petroleum Reserve (SPR) Program - Final Report, prepared by Sandia National Laboratories for the US Department of Energy, June 1979.

2. J. R. Tillerson, "Geomechanics Investigations of SPR Crude Oil Storage Caverns," invited paper presented at Solution Mining Research Institute Fall Meeting, Toronto, Canada, October 1979.

3. Strategic Petroleum Reserve - Annual Report, DOE/RA-0004/1(77), DOE/SPRO, February 1978.

4. Strategic Petroleum Reserve - Annual Report, DOE/US-003, DOE/SPRO, February 1979.

5. Strategic Petroleum Reserve Annual Report, DOE/RA-0047, DOE/SPRO, February 1980.

6. Gulf Interstate Engineering Company, Solution Cavern Certificates of Usability and Integrity for West Hackberry Site, 1977.

7. L. Sevenker, "The Department of Energy Strategic Petroleum Reserve," presented to Solution Mining Research Institute, Mexico City, Mexico, January 17-18, 1979.

8. Systems Integration and Engineering Support Study for the Strategic Petroleum Reserve (SPR) Program - Final Report, SAND79-0637 (Albuquerque, NM: Sandra National Laboratories, June 1979).

9. W. R. Wawersik, D. W. Hannum, H. S. Lauson, Compression and Extension Data for Dome Salt from West Hackberry SAND79-0668 (Albuquerque, NM: Sandia National Laboratoiies, September 1980).

10. R. W. Bild, Chemistry and Mineralogy of Three Core Samples from the SPR West Hackberry Salt Dome Site (Albuquerque, NM: Sandia National Laboratories SAND report, to be published).

11. R. W. Bild, Chemistry and Mineralogy of Samples from the Strategic Petroleum Reserve Bryan Mound Site, SAND80-1258 (Albuquerque, NM: Sandia National Laboratories, August 1980).

BIBLIOGRAPHY

Beasley, R. R., Salt Properties for Bryan Mound Dome, (Section 2 of 2) (Albuquerque, NM: Sandra National Laboratories, October 1980).

Bild, R. W., unpublished data, 1979.

Braitsch, O., Salt Deposits - Their Origin and Composition, Springer-Verlag, 1971.

Dreyer, W., "Zur Druckfestigkeit von Salzgesteinen," Kali and Steinsalz, Heft 7, 242-243, 1961.

Dreyer, W., The Science of Rock Mechanics, Trans. Tech. Publications, 1972.

Federal Energy Administration (now the US Department of Energy), Strateqic Petroleum Reserve Office, Strateqic Petroleum Reserve - Final Environmental Impact Statement, West-Hackberry Salt Dome, FES 76/77-4, 1977.

Hansen, F. D., Quasi-static and Creep Deformation Characteristics of Bedded Salt from the Carey Mine Near Lyons, Kansas, Tech Memo Report RSI-0067 (Rapid City, SD: RE/SPEC, Inc., 1978).

Hansen, F. D., Case History Rock Mechanics Examination of the Jefferson Island Salt Mine: II Laboratory Evaluation of Strength and Creep Deformation Characteristics of Dome Salt Under Confining Pressure, Tech Memo Report RSI-0057 (Rapid City, SD: RE/SPEC, Inc., 1978).

Herrmann, W., W. R. Wawersik, and H. S. Lauson, Creep Curves and Fitting Parameters for Southeastern New Mexico Bedded Salt, SAND80-0087 (Albuquerque, NM: Sandra National Laboratories, 1980).

Herrmann, W., W. R. Wawersik, and H. S. Lauson, Analysis of Steady State Creep of Southeastern New Mexico Bedded Salt, SAND80-0558 (Albuquerque, NM: Sandra National Laboratories, 1980).

Jacobs/D'Appolonia Consulting Engineers, Thermal Analyses, Stability Analyses, and Recertification Requirements, Cavern #6, West Hackberry Site, Cameron Parish, Louisiana, J/D-R--8, Technical Direction #J/D-17, 1979.

Jefferson, T. H., TJMARl - A FORTRAN Subroutine for Nonlinear Least Squares Parameter Estimation, SLA73-0305 (Albuquerque, NM: Sandia Laboratories, 1974).

Lomenick, T. F., "Laboratory Pillar Model Experiments,ll in Project Salt Vault: A Demonstration of the Disposal of High Activity Solidified Wastes in Underground Salt Mines, R. L. Bradshaw and W. C. McClain, eds, ORNL-4555 (Oak Ridge: Oak Ridge National Laboratory, 1971).

Obert, L., "Deformational Behavior of Model Pillars Made from Salt, Trona and Potash Ore," Proc. 6th US Rock Mech. Symposium (Rolla, MO: University of Missouri, 1964).

PB/KBB, Strategic Petroleum Reserve Program - Salt Dome Geology and Cavern Stability Analysis, Final Report to the US Department of Energy, August 1978.

Tillerson, J. R. and P. D. Hilton, "Long-Term Cavern Stability Evaluation,ll Appendix E in Systems Integration and Engineering Support Study for the Strategic Petroleum Reserve (SPR) Program - Final Reoort SPR Project Division 4701, eds, SAND79-0637 (Albuque>que; NM: Sandia National Laboratories, 1979).

Wawersik, W. R., Indirect Deformation (Strain) Measurements and Calibrations in Sandia Triaxial Apparatus for Rock Testing to 250oC, SAND79-0114 (Albuquerque, NM: Sandia National Laboratories, 1979).

Wawersik, W. R. and D. W. Hannum, "Mechanical Behavior of New Mexico Rock Salt in Triaxial Compression to 200°C," J Geophy Res 85:B2, 1980.

Wawersik, W. R., D. W. Holcomb, H. S. Lauson, and D. W. Hannum, Quasi-Static and Creep Data for Dome Salt from Bryan Mound, Texas, SAND80-1434 (Albuquerque, NM: Sandia National Laboratories, 1980).

Weertman, J., "Dislocation Climb Theory of Steady-State Creep," Trans. AIME, 61, 1968.

TABLE 1

TEST MATRIX

Test I.D.	Description of Test
4Q/6C-2206/O/22	Unconfined quasi-static compression, $\sigma_3 = 0$, $T = 22^{o}C$
4Q/8A-2302/O/60	Unconfined quasi-static compression, $\sigma_3 = 0$, $T = 60^{o}C$
4Q/8A-2301/2.0/22	Quasi-static triaxial compression, $\sigma_2 = \sigma_3 = 2000$ psi, $T = 22^{o}C$
4Q/6C-2208/2.0/60	Quasi-static triaxial compression, $\sigma_2 = \sigma_3 = 2000$ psi, $T = 60^{o}C$
3.5QE/6C-2241A/2.0/22	Quasi-static triaxial extension, $\sigma_2 = \sigma_1 = 2000$ psi, $T = 22^{o}C$
3.5QE/6C-2223/2.0/60	Quasi-static triaxial extension, $\sigma_2 = \sigma_1 = 2000$ psi, $T = 60^{o}C$
3.5C/6C-2241/2.0/22	Triaxial compression creep, $\sigma_2 = \sigma_3 = 2030$ psi, $(\sigma_1 - \sigma_3) =$ 2960 psi, $T = 22^{o}C$
3.5C/6C-2201/2.0/60	Triaxial compression creep, $\sigma_2 = \sigma_3 = 2030$ psi, $(\sigma_1 - \sigma_3) =$ 2900 psi, $T = 60^{o}C$
3.5CE/6C-2225/2.0/22	Triaxial extension creep, $\sigma_2 = \sigma_1 = 1990$ psi, $(\sigma_1 - \sigma_3) =$ 2900 psi, $T = 22^{o}C$
3.5CE/6C-2194/2.0/60	Triaxial extension creep, $\sigma_2 = \sigma_1 = 2070$ psi, $(\sigma_1 - \sigma_3) =$ 2890 psi, $T = 60^{o}C$

TABLE 2

MAXIMUM STRESSES AND STRAINS OF QUASI-STATIC TESTS
(SUBSCRIPT u PERTAINS TO ULTIMATE STRESS AND STRAIN VALUES)

	u3 (psi)	("l $- \sigma_3)_u$ (psi)	$(e_1)_u$ (%)	$(-e_3)_u$ (%)	$(\gamma)_u$ (%)	$(e)_u$ (%)	$(e)^*_{um}$ (%)
4Q/6C-2206/O/22	0	3790	2.5	4.0	6.5	-5.5	
4Q/8A-2302/0/60	0	3540	5.0	5.9	10.9	-6.8	-5.5
4Q/8A-230-l/2.0/22	2000	>8570	>14.3	>8.3	>22.6	-2.3	-2.4
4Q/6C-2208/2.0/60	2000	>7540	>25.4	>14.1	>39.5	-2.8	-3.9
3.5QE/6C-2241/2.0/22	2000	>6740	>3.5	>c.o	>9.5	1.0	0.4
3.5QE/6C-2223/2.0/60	2000	>5060	>3.8	>6.4	>10.2	1.2	-0.1

---

* Total volumetric strain estimates based on selected measurements of final specimen dimensions.

TABLE 3

SUMMARY OF DEFORMATION CHARACTERISTICS OF WEST HACKBERRY DOME SALT UPON FIRST LABORATORY LOADING AND LIST OF ELASTIC CONSTANTS

Test I.D.	σ_3 (psi)	Secant Modulus (10^6 psi)/Princ. Strain Ratio $500 \le \Delta\sigma$(psi) ≤ 1000	Secant Modulus (10^6 psi)/Princ. Strain Ratio $500 \le \Delta\sigma$(psi) ≤ 2000	Elastic (unloading) Constants E(10^6 psi)/ν
4Q/6C-2206/0/22	0	0.22/-0.30	0.68/-0.68	(3.7/0.65)*
4Q/8A-2302/0/60	0	0.16/-0.56	0.32/-0.71	(5.6/-)*
4Q/8A-2301/2.0/22	2000	1.75/-0.63	0.90/-0.52	$5.55^{+0.06}_{-0.22}/0.33^{+0.02}_{-0.06}$
4Q/6C-2208/2.0/60	2000	1.83/-0.30	1.05/-0.37	$5.67^{+0.25}_{-0.20}/0.31^{+0.3}_{-}$

*Measurement made past the ultimate stress.

TABLE 4

SUMMARY OF DATA OF CREEP EXPERIMENTS

Test I.D.	$(\sigma_1 - \sigma_3)$ (psi)	σ_3 (psi)	Initial Loading Rate (psi/s)	Test Duration (hrs)	Initial Strains (%) e_1	$-e_3$	Min. Observed Axial Creep Rate $\dot{e}_x$
3.5C/6C-2243/2.0/22	2960	2030	52.2	475	0.51	0.21	9.47E-9
3.5C/6C-2201/2.0/60	2900	2030	95.7	263	0.69	0.27	7.23E-8
3.5CE/6C-2225/2.0/22	2900	1990	30.5	262	0.13	0.18	1.19E-8
3.5CE/6C-2196/2.0/60	2890	2070	14.5	72*	0.25	0.37	5.97E-8

*Test run to 311 hours; however, loading piston bottomed out after 72 hours rendering subsequent data invalid.

TABLE 5

FITTING PARAMETERS FOR AXIAL CREEP STRAINS, e_x, ACCORDING TO EQUATIONS (1-5)

Using the Correspondences $e_x \leftrightarrow |e_t|$, $C_1 \leftrightarrow e_o$, $C_2 \leftrightarrow e_a$, $C_3 \leftrightarrow \xi$, $C_4 \leftrightarrow \dot{e}_s$ and $C_1' \leftrightarrow e_\theta'$, $C_2' \leftrightarrow \alpha$, $C_4' \leftrightarrow n$

Fit No. 1: $|e_x| = C_1 + C_2 (1 - \exp(-C_3 t) + C_4 t)$; Fit No. 2: $|e_x| = C_1' + C_2' \left(\frac{\sigma_1 - \sigma_3}{\mu}\right)^{3.0} t^{C_4'}$ where $\mu = 1.8 \times 10^6$ psi (shear modulus). t denotes time in seconds.

Test I.D.	File No.	Fit No.	Subscript of Constants 1	2	3	4	Standard Error of Fit
3.5C/6C-2243/2.0/22	CD8A	1	3.71E-3	1.06E-2	8.623-6	1.31E-8	0.4873-3
		2	3.94E-4	3.51E-3	3.00	0.528	0.394E-2
3.5CE/6C-2225/2.0/22	CD9A	1	6.33E-3	9.05E-3	9.28E-6	1.13E-8	0.4323-3
		2	4.28E-3	2.06E-4	3.00	0.393	0.2253-3
3.5C/6C-2201/2.0/60	CD6A	1	5.96E-3	2.633-2	3.00E-5	8.933-8	0.2303-2
		2	1.05E-2	4.99E-3	3.00	0.609	0.1733-2
3.5CE/6C-2196/2.0/60	CD7A	1	6.553-3	1.843-2	5.593-5	1.363-7	0.128E-2
		2	5.043-3	2.86E-4	3.00	0.481	0.2363-3

TABLE 6

INDICATOR PROPERTIES FOR ROCK SALT FROM WEST HACKBERRY, JEFFERSON ISLAND, AND LYONS[13,14]

Material Source	No. of Tests or Measurements	σ_3 (psi)	$(\sigma_1 - \sigma_3)^*_u$ (psi)	Secant Mod., E_s $500 \leq \Delta\sigma$ (psi) ≤ 2000 (10^6 psi)	Elastic Constants $E(10^6 \text{ psi})/\nu$	$(e_1)^*_u$ (%)	$\frac{d}{dt}(\sigma_1 - \sigma_3)$ (psi/s)
West Hackberry	1	0	3780	0.67	----	2.5	1
	1	2000	>8570	0.90	----	>14.3	1
	6	0-2000	----	----	$5.58^{+0.33}_{-0.25}/0.32^{+0.03}_{-0.05}$	----	>10
Jefferson Island	2	0	3120+15	0.19 ± 0.01	----	2.9	0.3
	1	0	3520	0.26	----	2.9	8.3
	1	1500	>9650	0.59	----	>21.5	8.3
	2	2000	>6900	0.39+0.06	----	>13.5	0.3
	6	0-2000			$3.03^{+0.94}_{-1.03}/0.42^{+0.09}_{-0.19}$	----	----
Lyons	3	0	3660^{+120}_{-190}			(3.5	-2.5
	2	500	----	0.55+0.1	----	----	-2.5
	7	500-5000	----	$>0.87 \pm {}^{0.35}_{-0.44}$		----	~2.5
	2	500-2000	----	----	1.54 ± 0.07/----	----	-2.5

*Subscripts u pertain to ultimate stress and strain values.

TABLE 7

DESCRIPTIONS OF SAMPLES RECEIVED FROM WEST HACKBERRY SALT DOME

SPR-1	WH-6C-2208	Piece of 4-in. dia core ranging from l/2 to l-3/8 in. (1.3 to 3.5 cm) thick. Grain size - about 0.4 in. (1 cm). Color - clear white. Weight - 385 g.
SPR-2	WH-6C-2241/3	Piece of 3-l/4-in.-dia core about 2 in. (5 cm) thick. Grain size - about 0.4 in. (1 cm). Color - white, perhaps a little darker than SPR-1. Weight - 591 g.
SPR-3	WH-6C-2208	Piece of 4-in.-dia core ranging from 7/8 to l-3/4 in. (2.2 to 4.4 cm) thick. Mostly clear halite, some dark streaks run through the core. Weight - 601 g.

TABLE 8

CHEMICAL COMPOSITION OF WEST HACKBERRY SALT CORE SAMPLES
(ALL VALUES ARE IN WEIGHT PERCENT)

Sample	Soluble Na^+	Soluble Ca^{++}	Soluble K^+	Soluble Cl^-	Soluble SO;	Insoluble	Sum	Total $CaSO_4$	
SPR-1 (WH-6C-2208)	37.7	0.272	0.001	58.5	0.65	1.87	99.0	2.79	
SPR-2 (WH-6C-2241/3)	37.5	0.271	0.001	57.9	0.66	2.54	98.9	3.47	3.8%
SPR-3 (WH-6C-2208)	36.5	0.360	0.001	57.4	0.86	3.90	99.0	5.12	

Other elements analyzed. All values in weight percent.

Sample	Soluble Li+	Soluble Sr^{++}	Soluble Br^-	Soluble Mg^{++}	Soluble HCO_3^-	Soluble CO;
SPR-1 (WH-6C-2208)	~0.001	L0.001	---	<1 x 10^{-4}	≤0.005	<0.005
SPR-2 (WH-6C-2241/3)	≤0.001	≤0.001	≤0.005*	≤1 x 10^{-4}	~0.005	≤0.005
SPR-3 (WH-6C-2208)	≤0.001	≤0.001	≤0.005*	≤1 x 10^{-4}	~0.005	≤0.005

*Bromine was detected above background, but at too low a level to permit accurate calculation of a concentration.

TABLE 9

CHEMICAL COMPOSITIONS OF WATER-SOLUBLE PORTIONS OF WEST HACKBERRY SALT CORES IN MOLAR UNITS

Sample	Na^+	Ca^{++}	K^+	Cl^-	$SO_4^=$
SPR-1 (WH-6C-2208)	1.640	0.00679	0.00003	1.650	0.0068
SPR-2 (WH-6C-2241/3)	1.631	0.00676	0.00003	1.633	0.0069
SPR-3 (WH-6C-2208)	1.588	0.00898	0.00003	1.619	0.0090

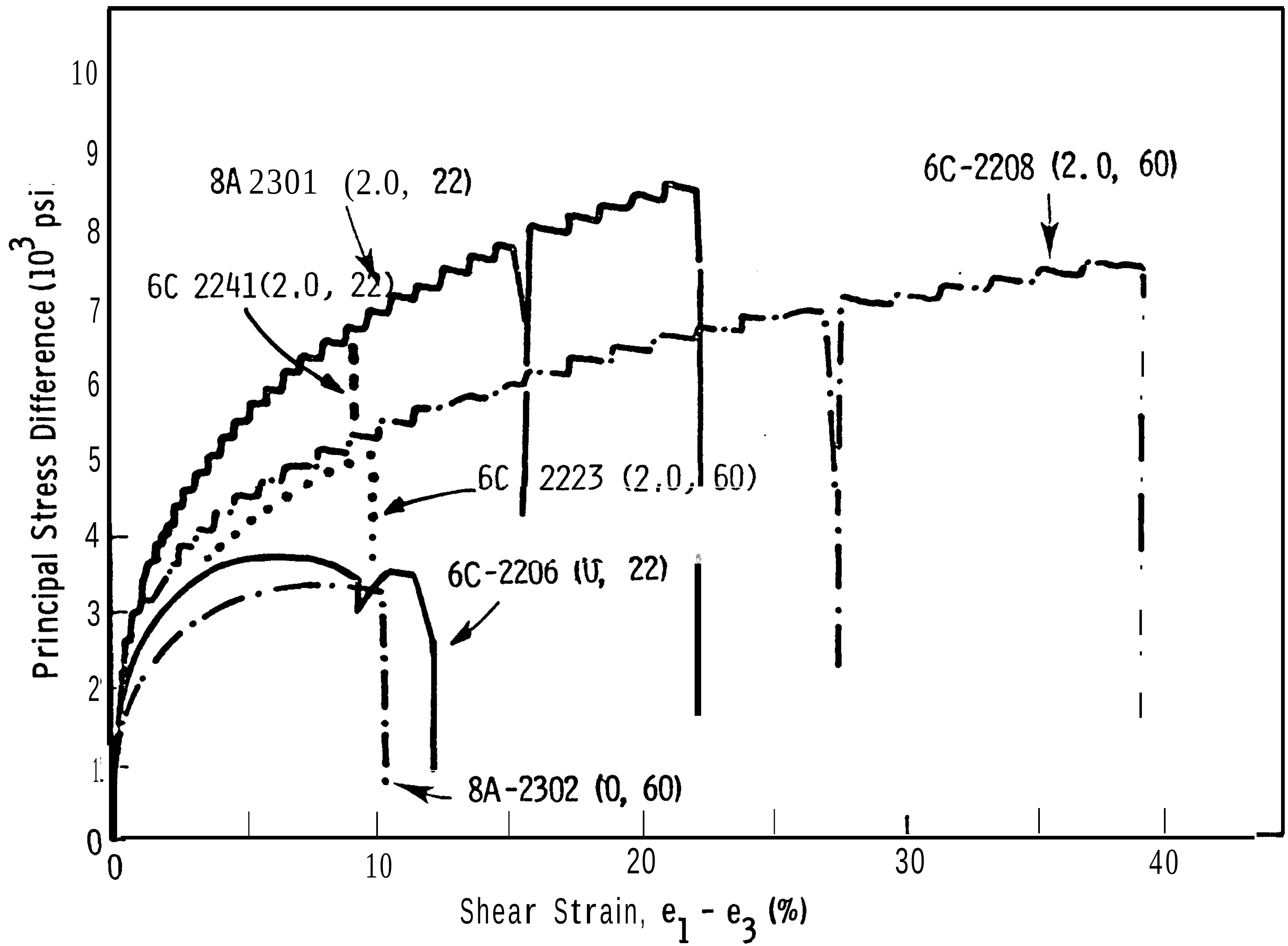

Figure 1
Principal Stress Difference Versus Shear Strain for Uniaxial and Triaxial Tests at 22° and 60°C

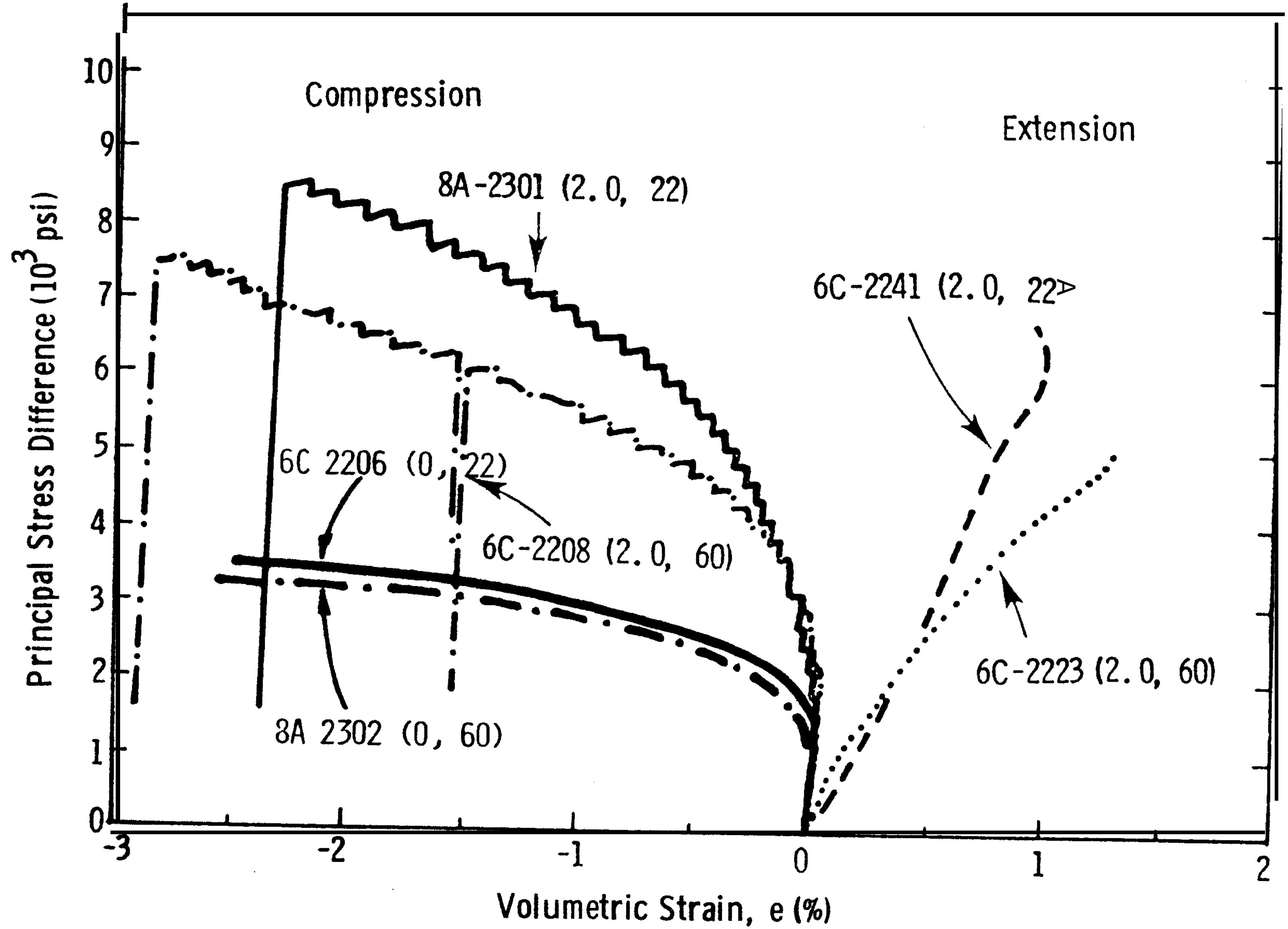

Figure 2
Principal Stress Difference Versus Volumetric
Strains for Uniaxial and Triaxial
Tests at 22^{o} and 60^{o}C

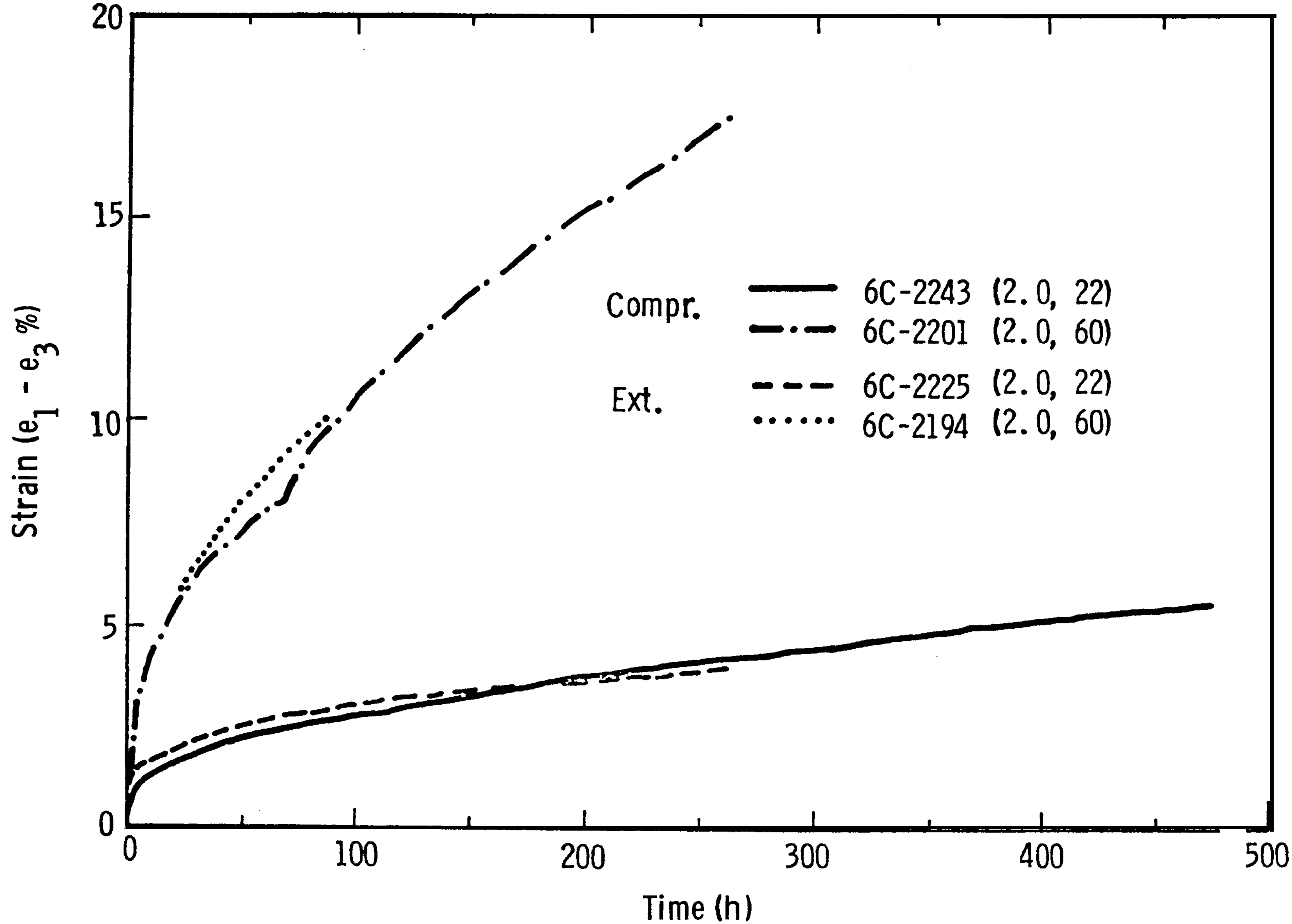

Figure 3
Shear Creep in Triaxial Compression
and Triaxial Extension
at 22° and 60°C

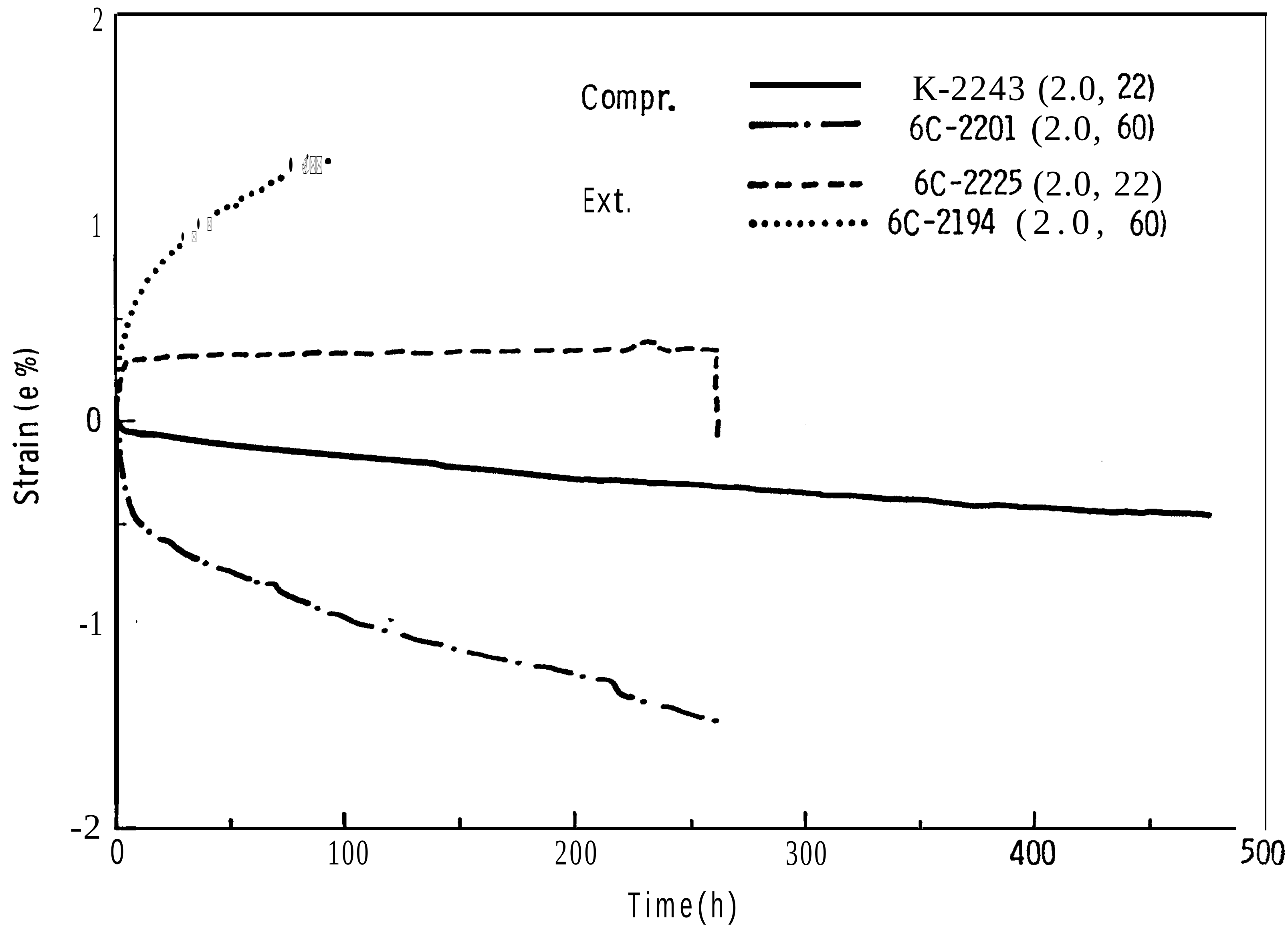

Figure 4
Volumetric Creep in Triaxial
Compression and Triaxial Extension
at 22° and 60°C

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